

# Searching for Electron Neutrino Appearance at ANL

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Mayly Sanchez  
Argonne/Iowa State

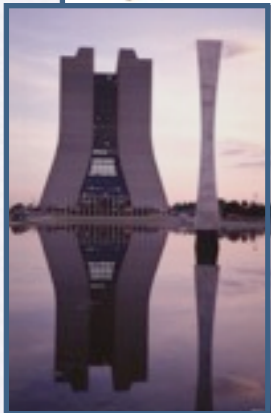
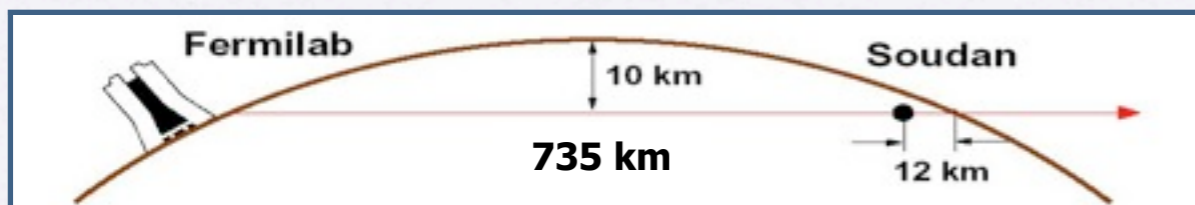
ANL DOE Site Visit  
September 23-24, 2009



# $\nu_e$ appearance in MINOS

- Produce a high intensity beam of muon neutrinos at Fermilab.
- Measure background at the Near Detector and use it to predict the Far Detector spectrum.
- If  $\nu_\mu$  oscillate to  $\nu_e$ , we will observe an excess over the predicted background in the data at the Far Detector in Soudan.

## Main Injector Neutrino Oscillation Search



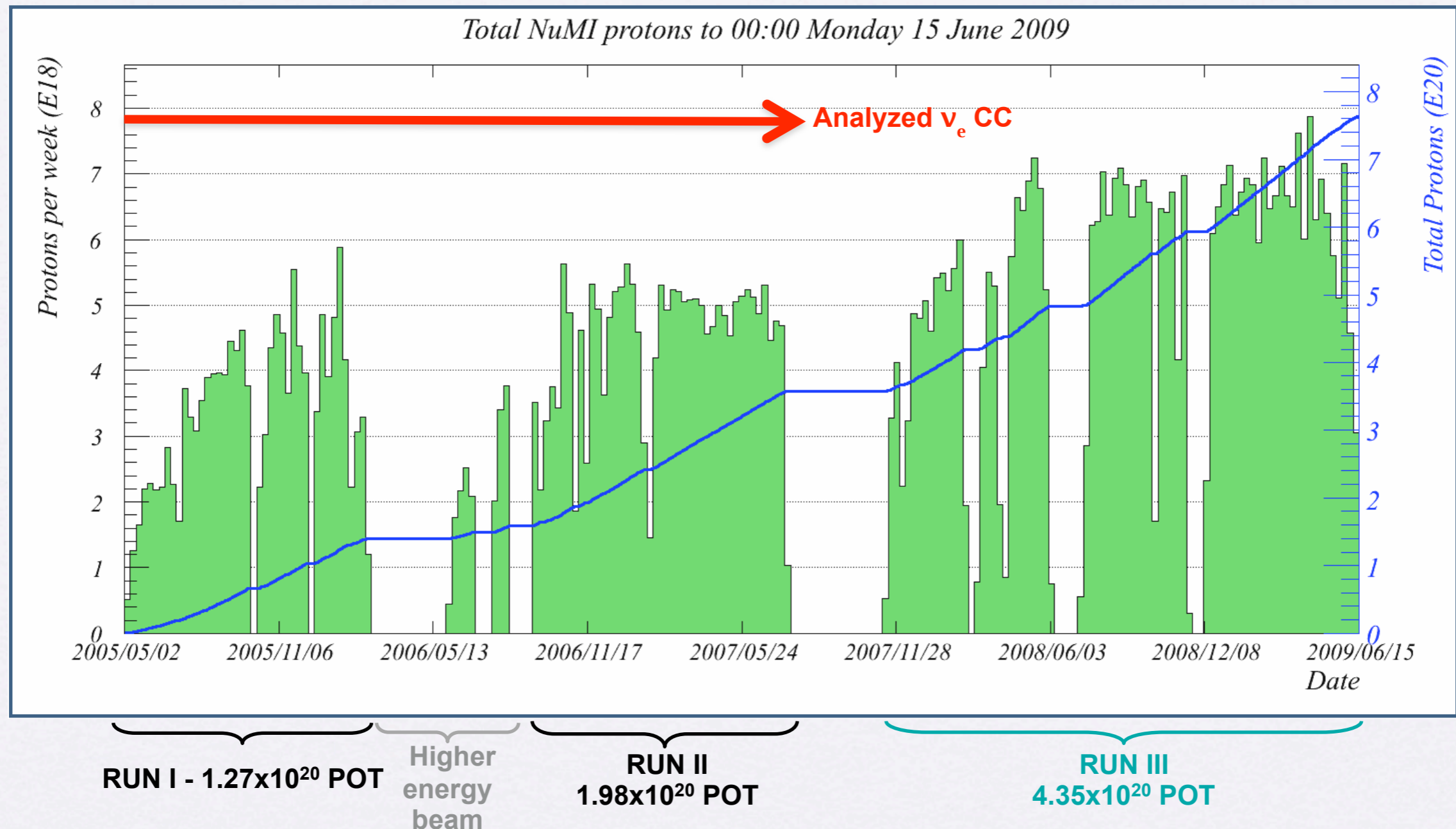
1st generation  
← long baseline →





# MINOS Running Status

Run II data analyzed, getting ready for **Run III** data



Run I+II -  $3.25 \times 10^{20}$  POT  $\rightarrow$  Run I+II+III -  $7.60 \times 10^{20}$  POT



# Searching for $\theta_{13}$ in MINOS & NOvA

- The probability of  $\nu_e$  appearance in a  $\nu_\mu$  beam:

$$A \equiv \frac{G_f n_e L}{\sqrt{2} \Delta} \approx \frac{E}{11 \text{ GeV}}$$

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$

$$\Delta \equiv \frac{\Delta m_{31}^2 L}{4E}$$

$$+ 2\alpha \sin \theta_{13} \cos \delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos \Delta$$

$$- 2\alpha \sin \theta_{13} \sin \delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin \Delta$$

- Searching for  $\nu_e$  events in MINOS & NOvA, we can access  $\sin^2(2\theta_{13})$ .
- Probability depends not only on  $\theta_{13}$  but also on  $\delta_{CP}$ . For large  $\theta_{13}$ , a measurements could be possible.
- \* Probability is enhanced or suppressed due to matter effects which depend on the mass hierarchy i.e. the sign of  $\Delta m_{31}^2 \sim \Delta m_{32}^2$  as well as neutrino vs anti-neutrino running.

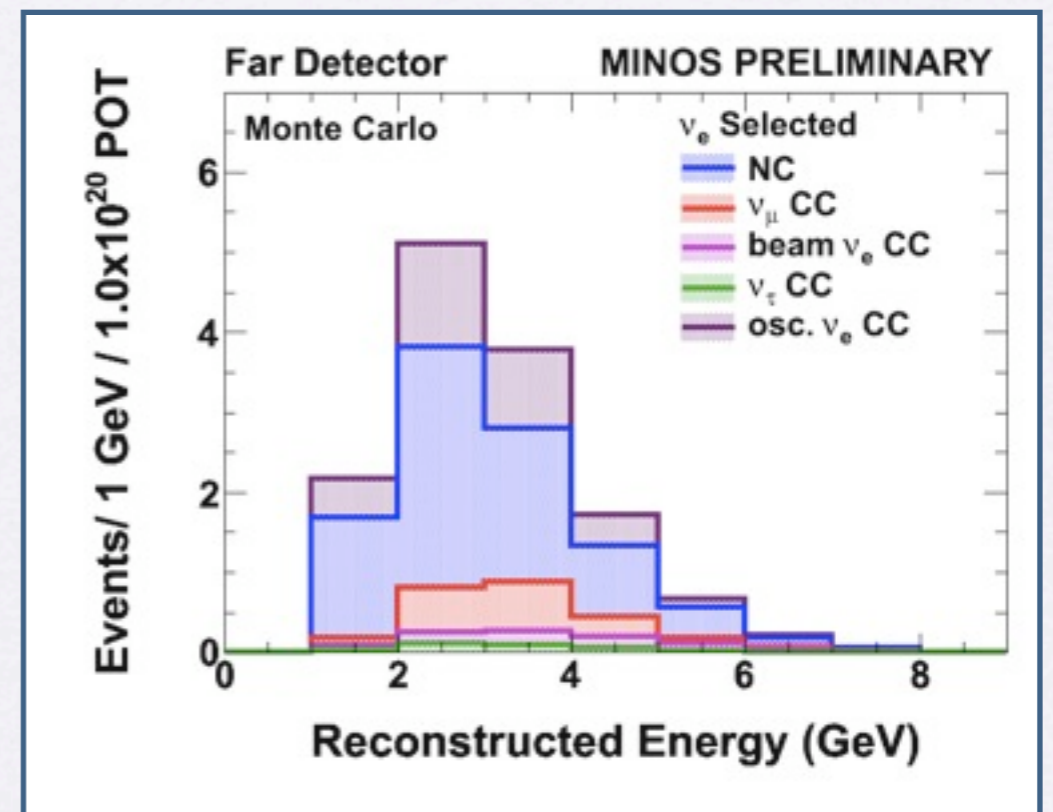
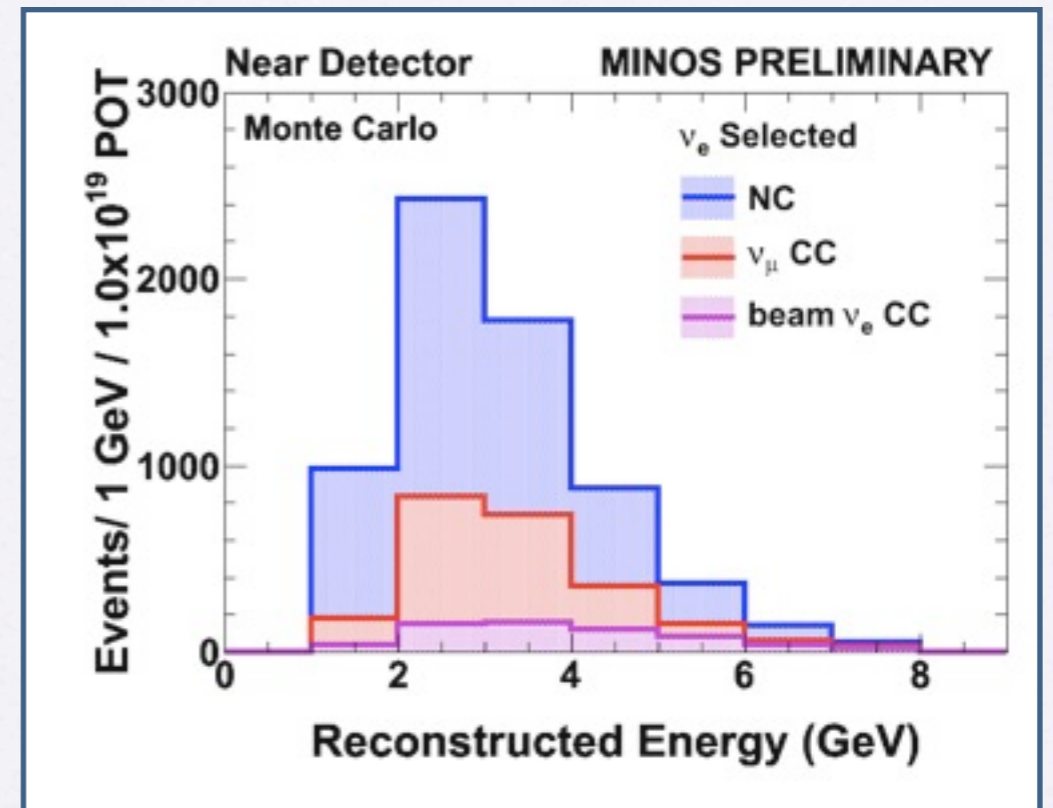
\* A 30% effect in NOvA, compared to 11% in T2K



# $\nu_e$ appearance in MINOS

- **Select  $\nu_e$  events** by finding electron candidates in the MINOS Detectors.
- **Measure the background** from events passing  $\nu_e$  selection in the Near Detector.
  - **Separate the main background components** NC,  $\nu_\mu$  CC and beam  $\nu_e$  CC since they extrapolate differently.
- **Extrapolate each background type** to the Far Detector taking into account  $\nu_\mu$  to  $\nu_\tau$  oscillations.
- **Look for an excess of  $\nu_e$  events** in the Far Detector data. Cut and count events.

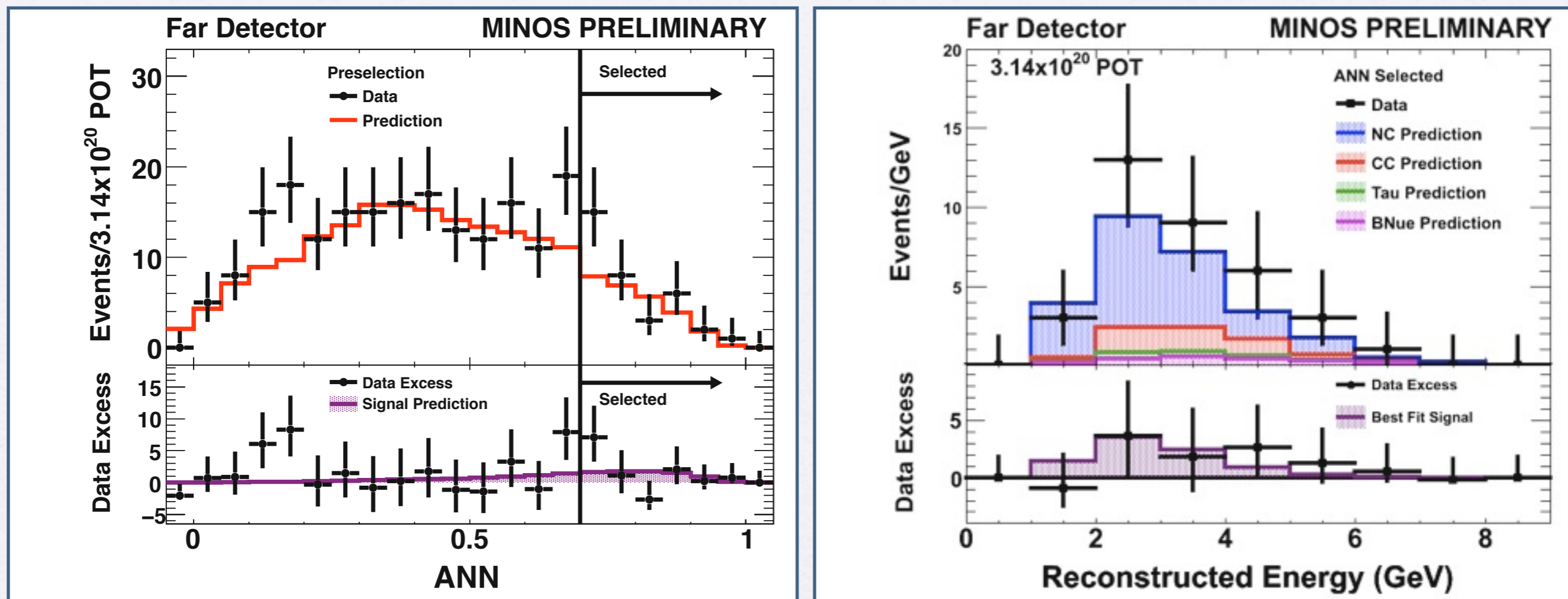
♦ **Measure  $\sin^2(2\theta_{13})$  !**





# $\nu_e$ -selected Far Detector Data

- We observe a total of **35 events** and expect  $27 \pm 5(\text{stat}) \pm 2(\text{sys})$  background events for  $3.14 \times 10^{20}$  POT.



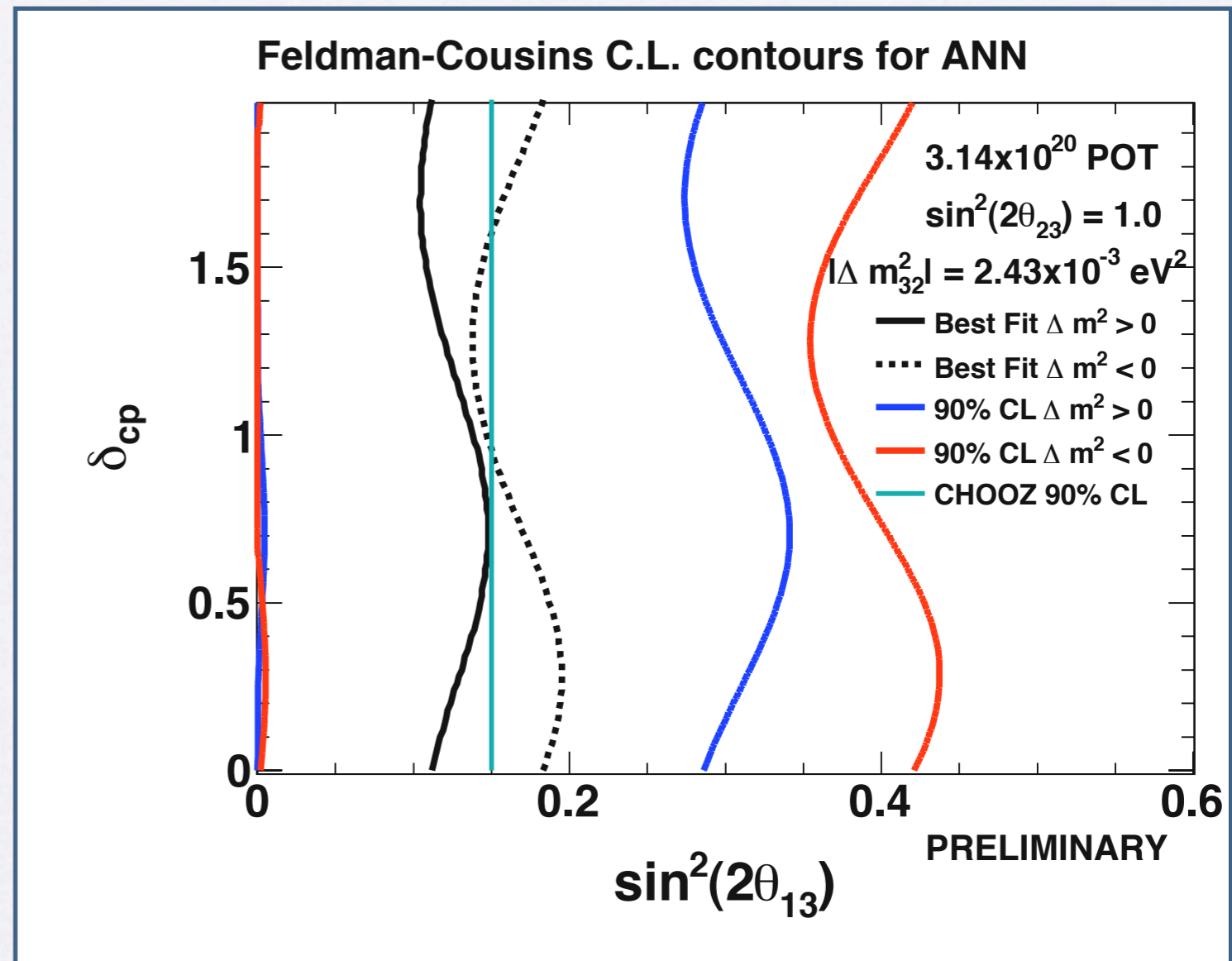
- Data outside signal region in Far Detector: muon removed and below signal region samples. Both consistent within  $1-2 \sigma$ .



# MINOS 90% CL in $\sin^2 2\theta_{13}$

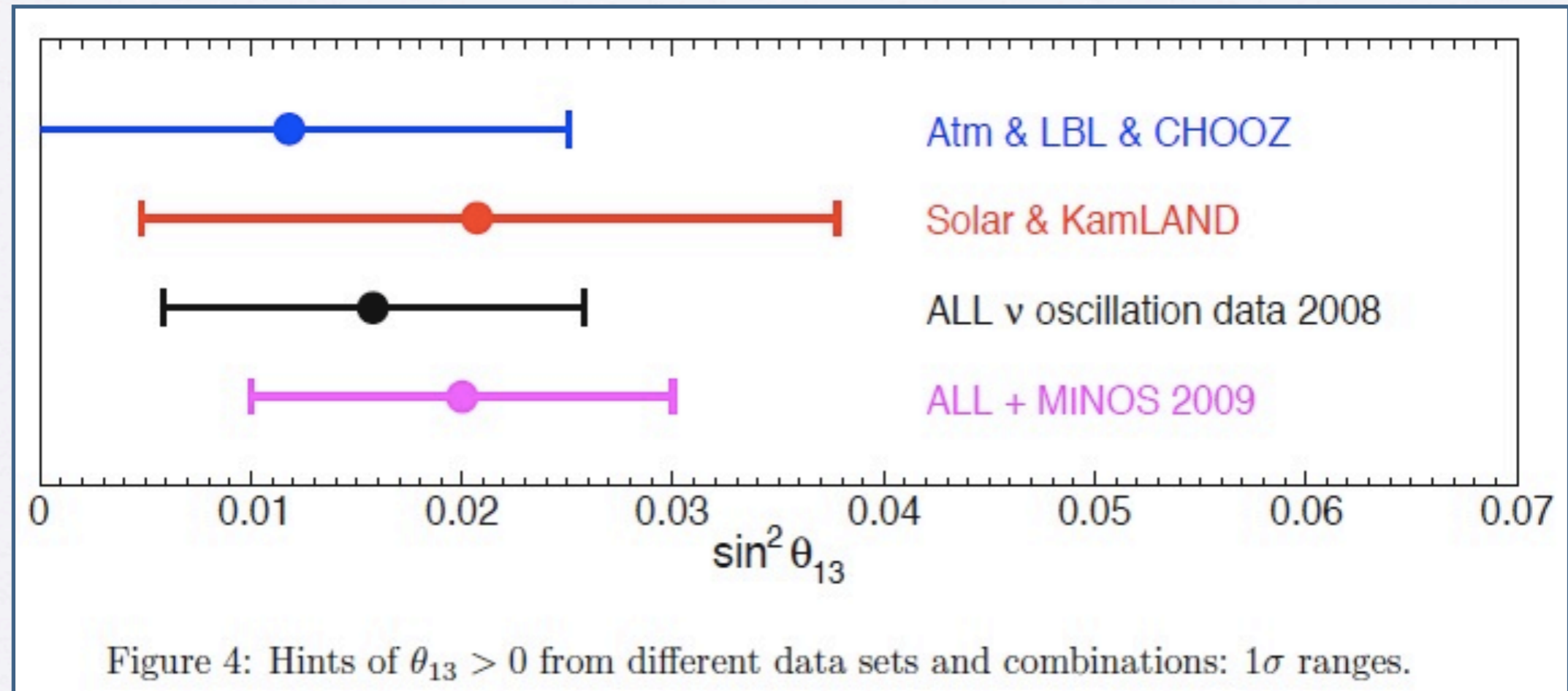
Fitting the oscillation hypothesis to our data

- Plot shows 90% CL limits in  $\delta_{CP}$  vs.  $\sin^2 2\theta_{13}$ 
  - shown at the MINOS best fit value for  $\Delta m^2_{32}$  and  $\sin^2 2\theta_{23}$ .
  - for both mass hierarchies
- A Feldman-Cousins method was used.
- Results are consistent with a secondary selection and background separation method.





# MINOS contribution to the global fits



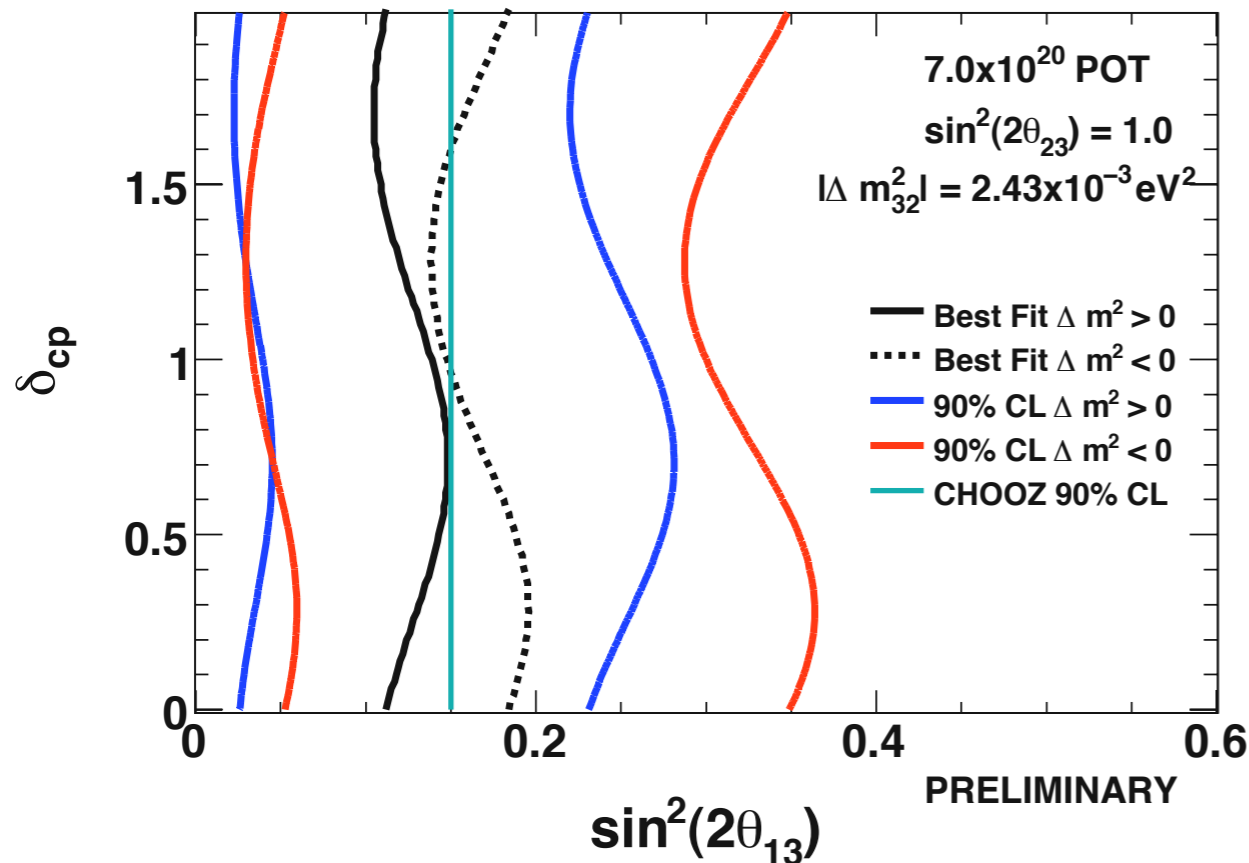
- Recent global fit to the world data by Fogli et al. (arxiv0905.3549).
- $\sin^2(2\theta_{13})=0$  disfavored at  $2\sigma$ .
- Central value for  $\sin^2(2\theta_{13}) = 0.08$  (or  $\sin^2(\theta_{13})=0.02$ ).



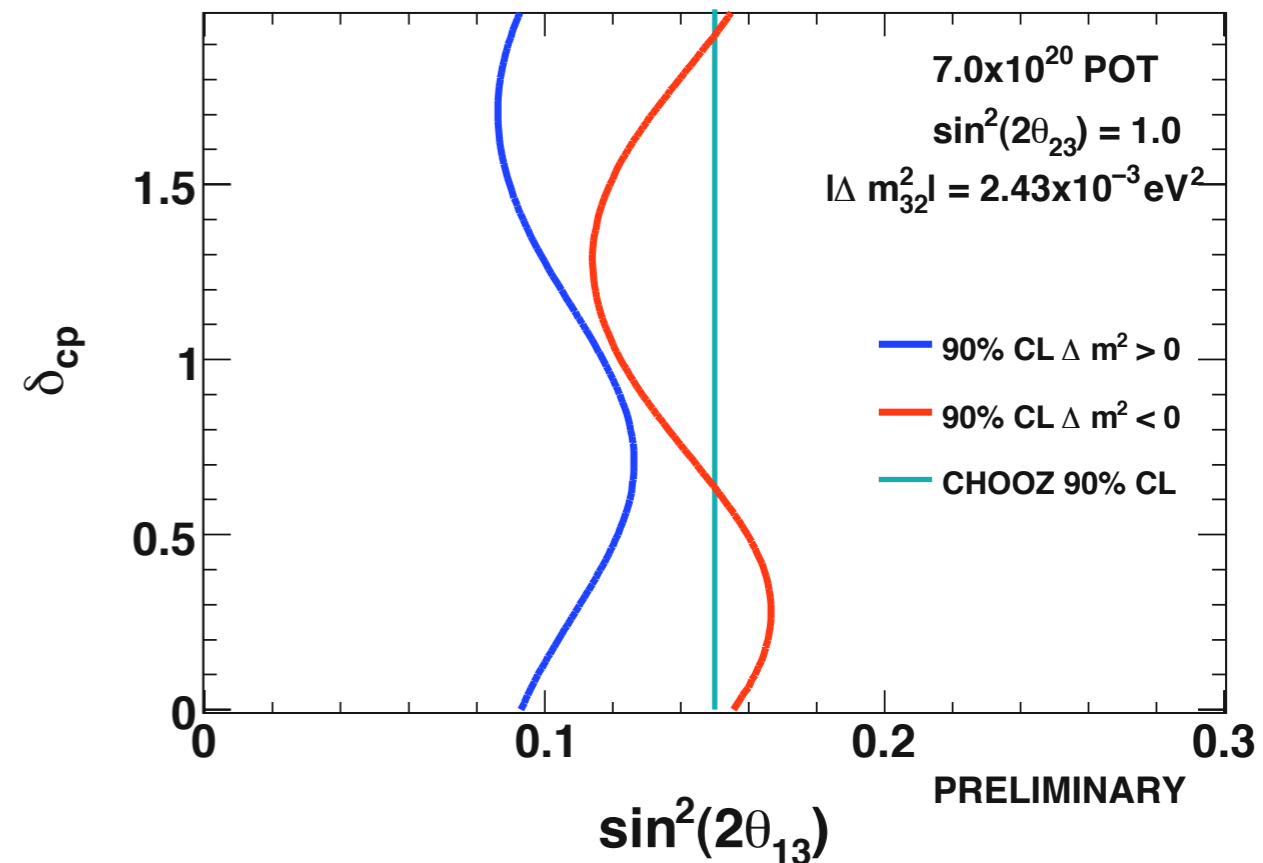
# Future 90% CL contours

$7.0 \times 10^{20}$  POT

Potential Feldman–Cousins C.L. contours for ANN



Potential Feldman–Cousins C.L. contours for ANN



Future measurement if data  
excess persists.

Future limit if excess cancels  
with more data.

We have doubled the data in before the shutdown:  
**Expect next results with  $7.6 \times 10^{20}$  POT !**



# $\nu_e$ MINOS contributions and prospects at ANL

- M. Sanchez : Co-leader of the  $\nu_e$  appearance analysis group in MINOS ('04-'09). Co-author of the paper being submitted to PRL as we speak.
  - X. Huang: Important contributions to the analysis, in particular studies on the intensity systematic.
  - M. Betancourt: Added a fundamental cut to the analysis as a graduate summer student. Now at UMN.
- New  $\nu_e$  appearance analysis will use twice as much data and requires better understanding of systematics.
  - X. Huang: Calibration systematics, signal efficiency systematics. Analysis file production.
  - S. Budd: Beam systematics, including the understanding flux differences in the new data and MC and beam  $\nu_e$  CC.

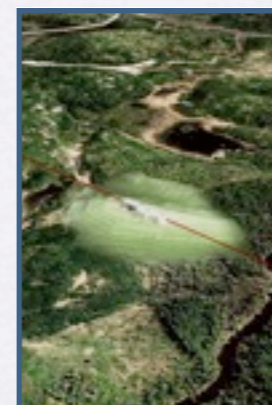


# NOvA in a nutshell

- Use existing high intensity beam of muon neutrinos at Fermilab.
- Construct two detectors, bigger detector off the main axis of the beam.
  - Location reduces background for the search.
- If neutrinos oscillate, electron neutrinos are observed at the Far Detector in Ash River, 810 km away.

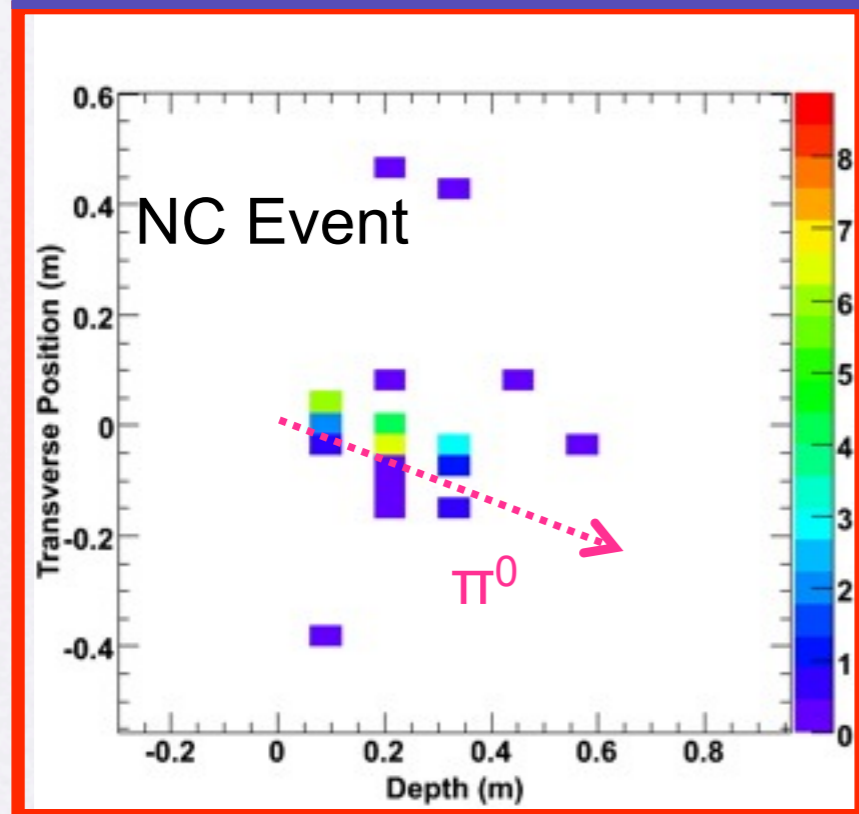
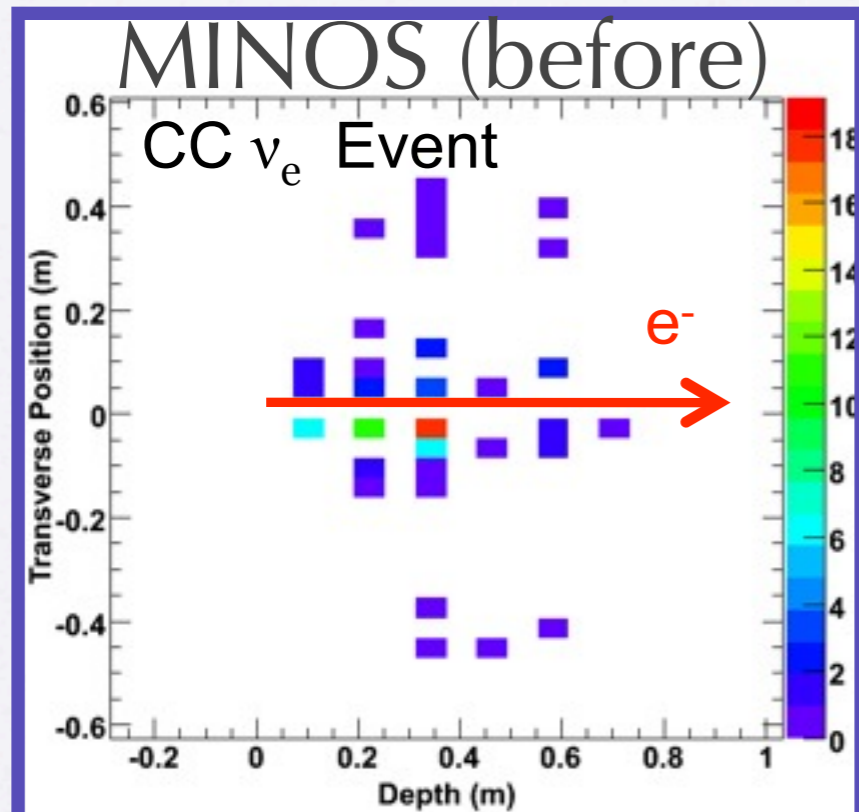


2nd generation  
← long baseline →

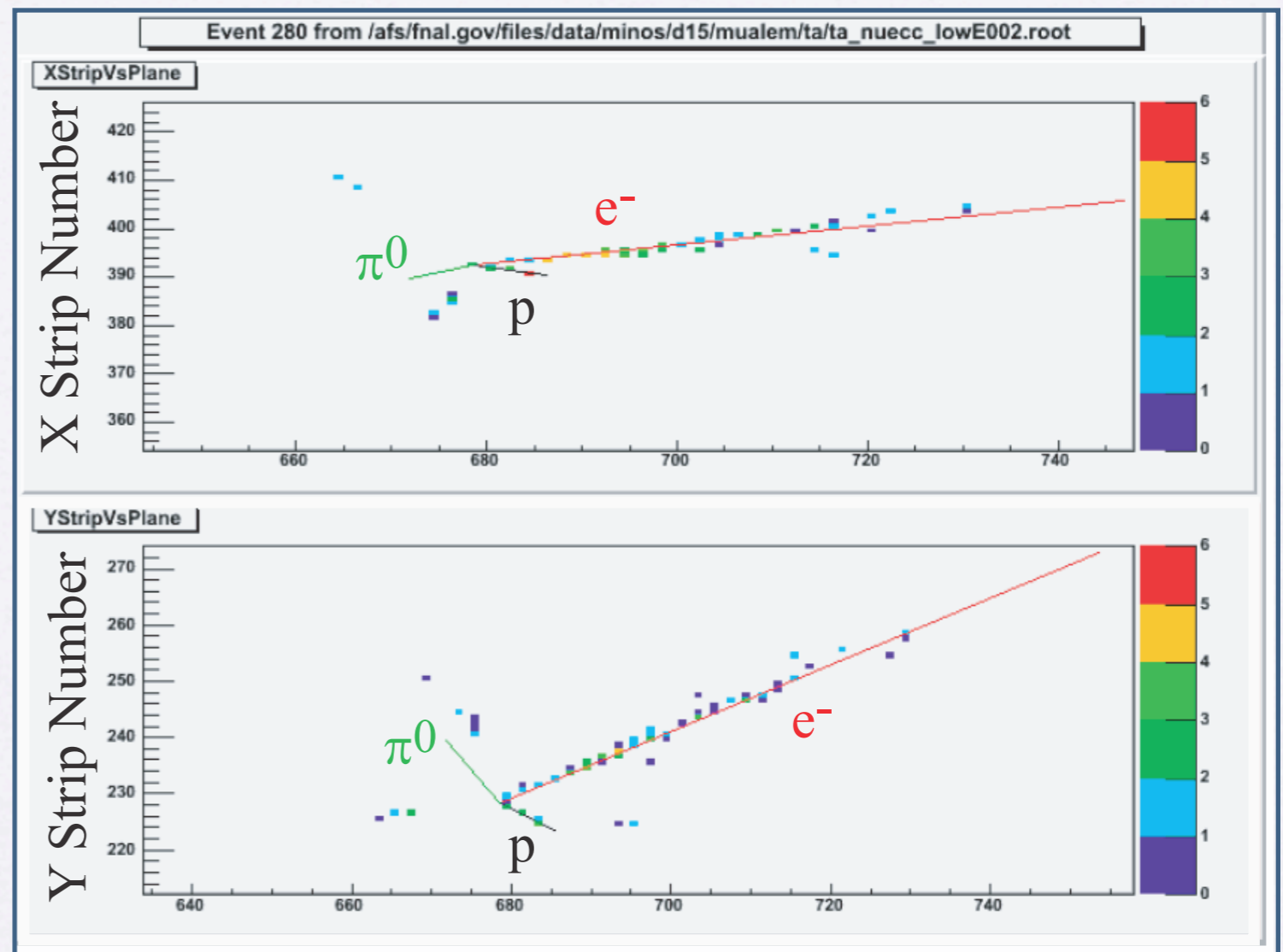




# Electrons and neutral pions



NOvA (after)

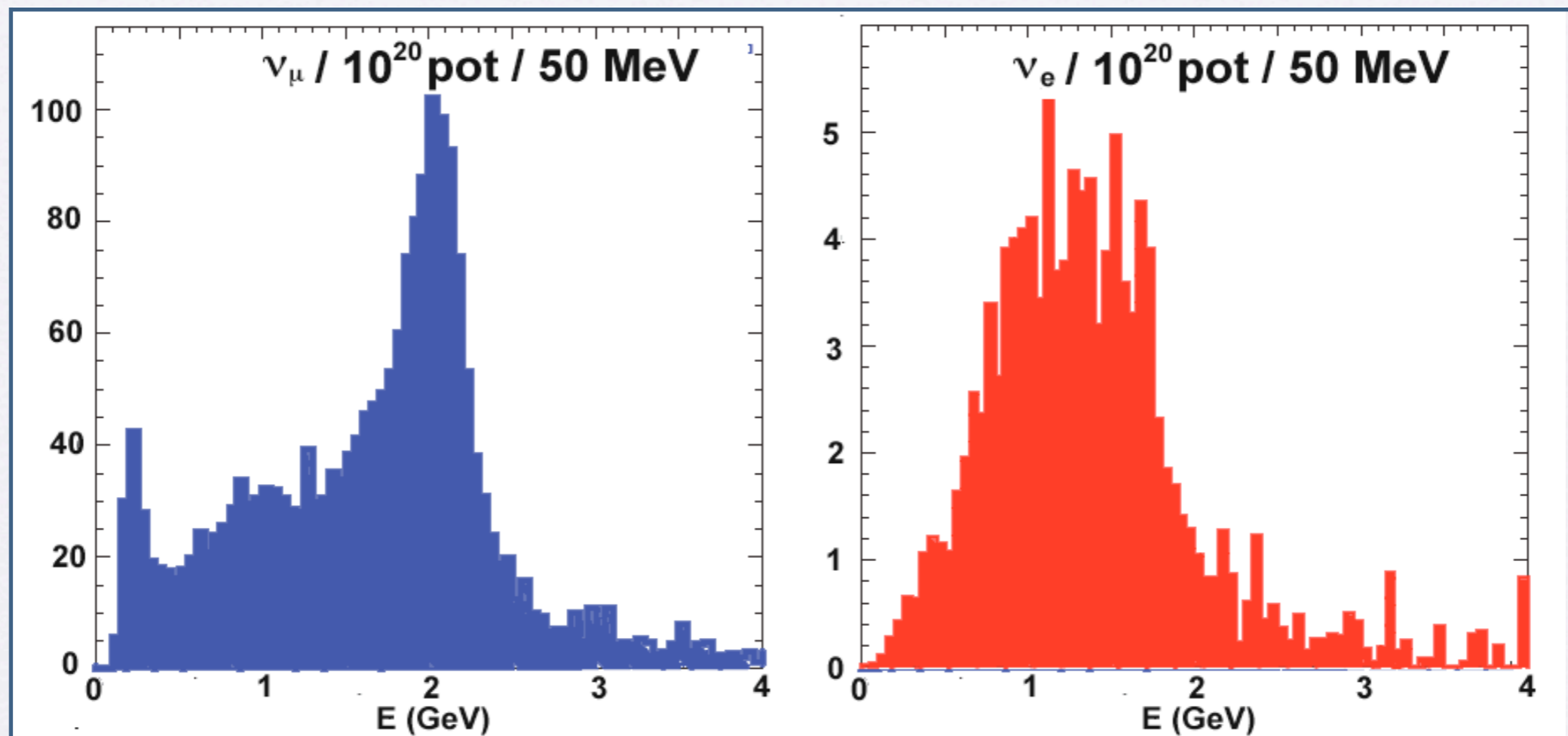


NOvA is designed to search for electrons.



# Integration Prototype Near Detector

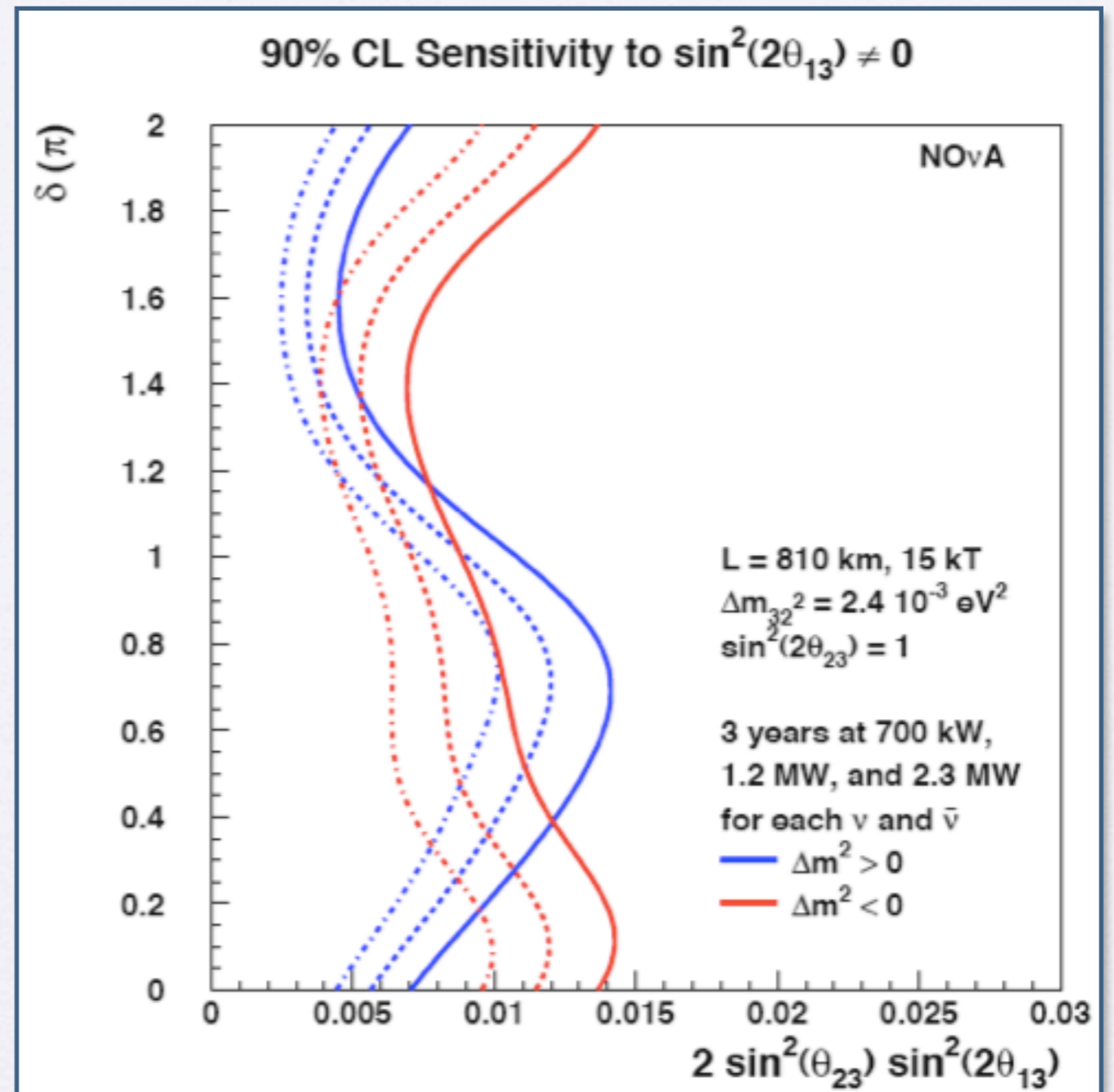
- Full Near Detector will be placed on the surface outside of the MINOS building at 107 mrad off-axis from the NuMI beam, dominated by kaon decays.
- Neutrino data will be available to validate reconstruction and simulations in 2010!
- Cross-section measurements could be interesting!





# NOvA sensitivity for $\theta_{13}$

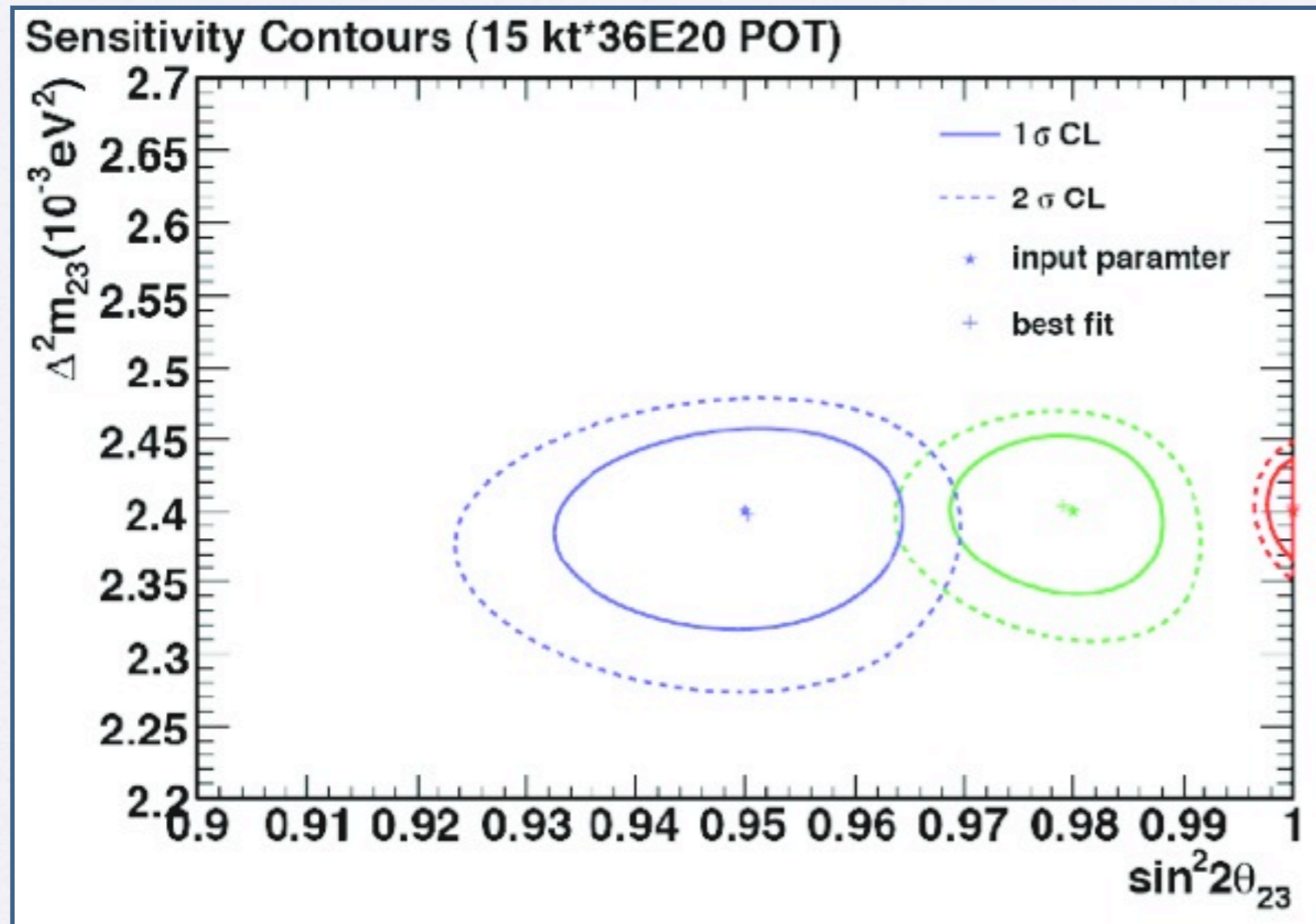
- NOvA is sensitive to electron neutrino appearance down by an order of magnitude at 90% CL.
- Reach is for 3 years of running  $\nu_\mu$  and  $\bar{\nu}_\mu$ .
- Note contours for different beam upgrades.





# Is the mixing maximal?

Sensitivity on  $\sin^2 2\theta_{23}$



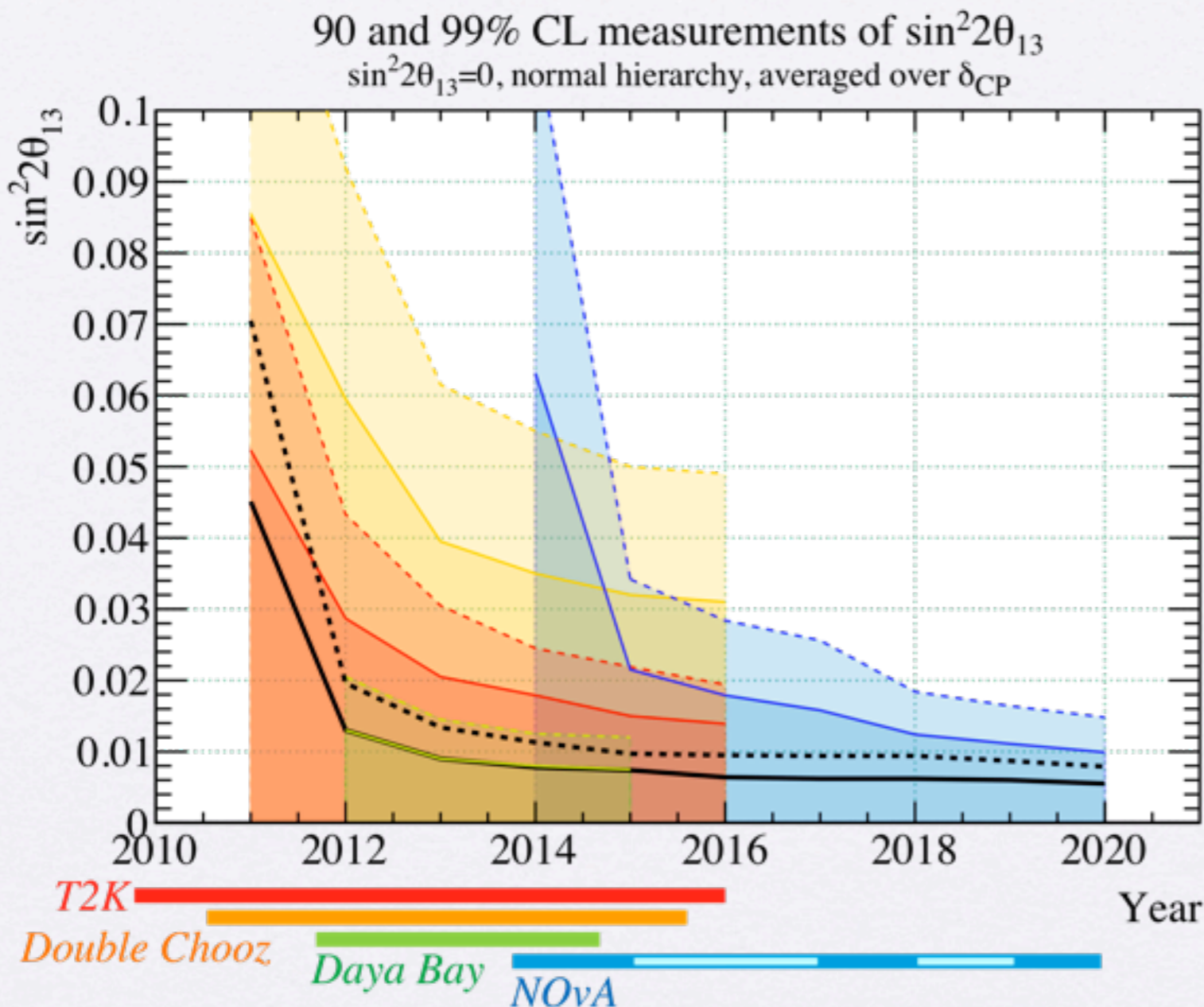
If combined with Double Chooz/Daya Bay it can break the ambiguity in  $\theta_{23}$ .

- NOvA's narrow band beam centered at the peak of the oscillation, allows for a 1% disappearance measurement.
- Improve one order of magnitude in  $\sin^2 2\theta_{23}$ .



# NOvA's physics reach

Assuming 700 kW beam

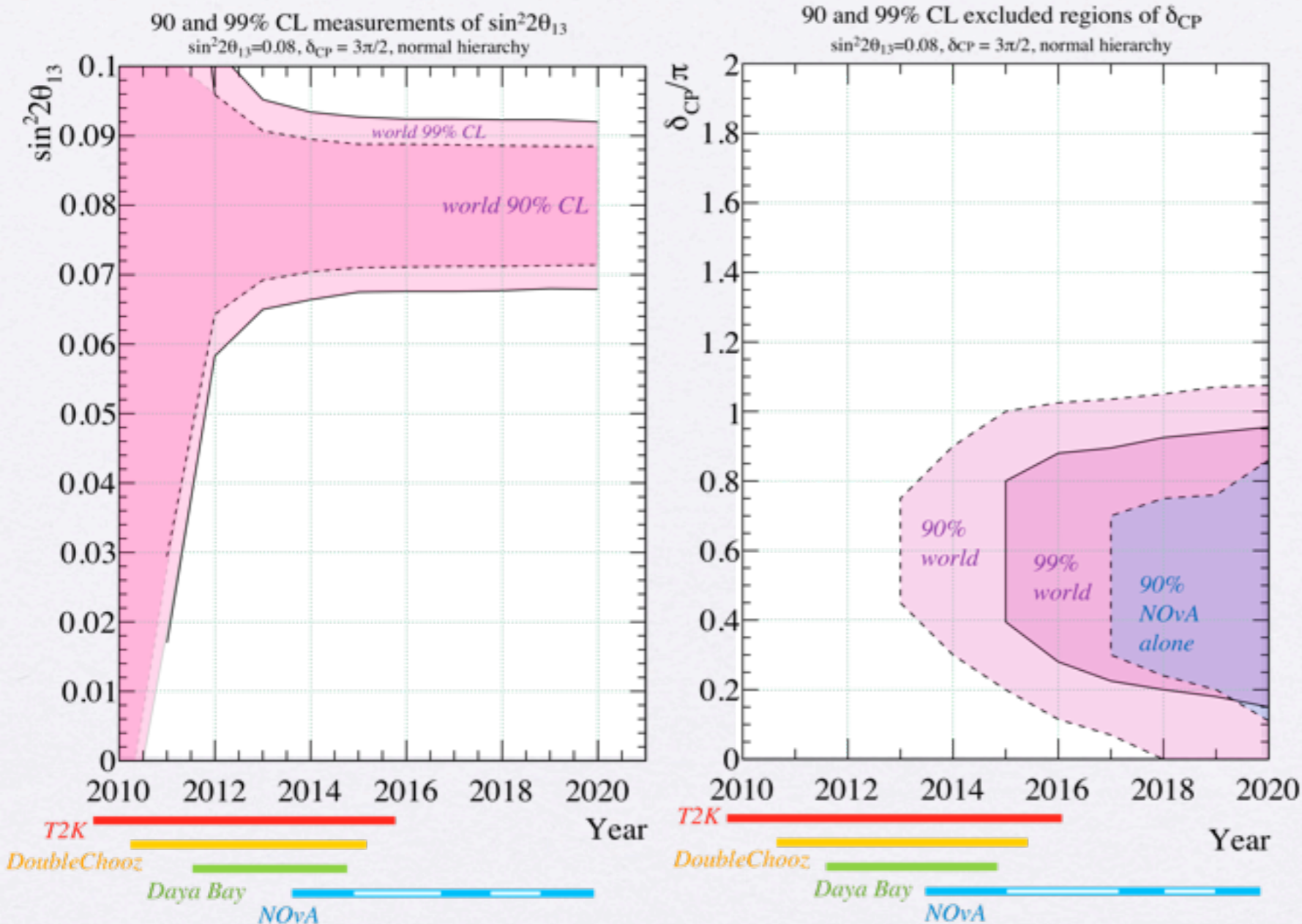


- Do interpret the dates with the appropriate amount of salt:
- Plots for data taken not analyses published.
- Schedules always change.
- If  $\sin^2 2\theta_{13}$  high, NOvA reaches it to make precision measurement.



# What if the mixing is large?

$$\sin^2 2\theta_{13} = 0.08$$

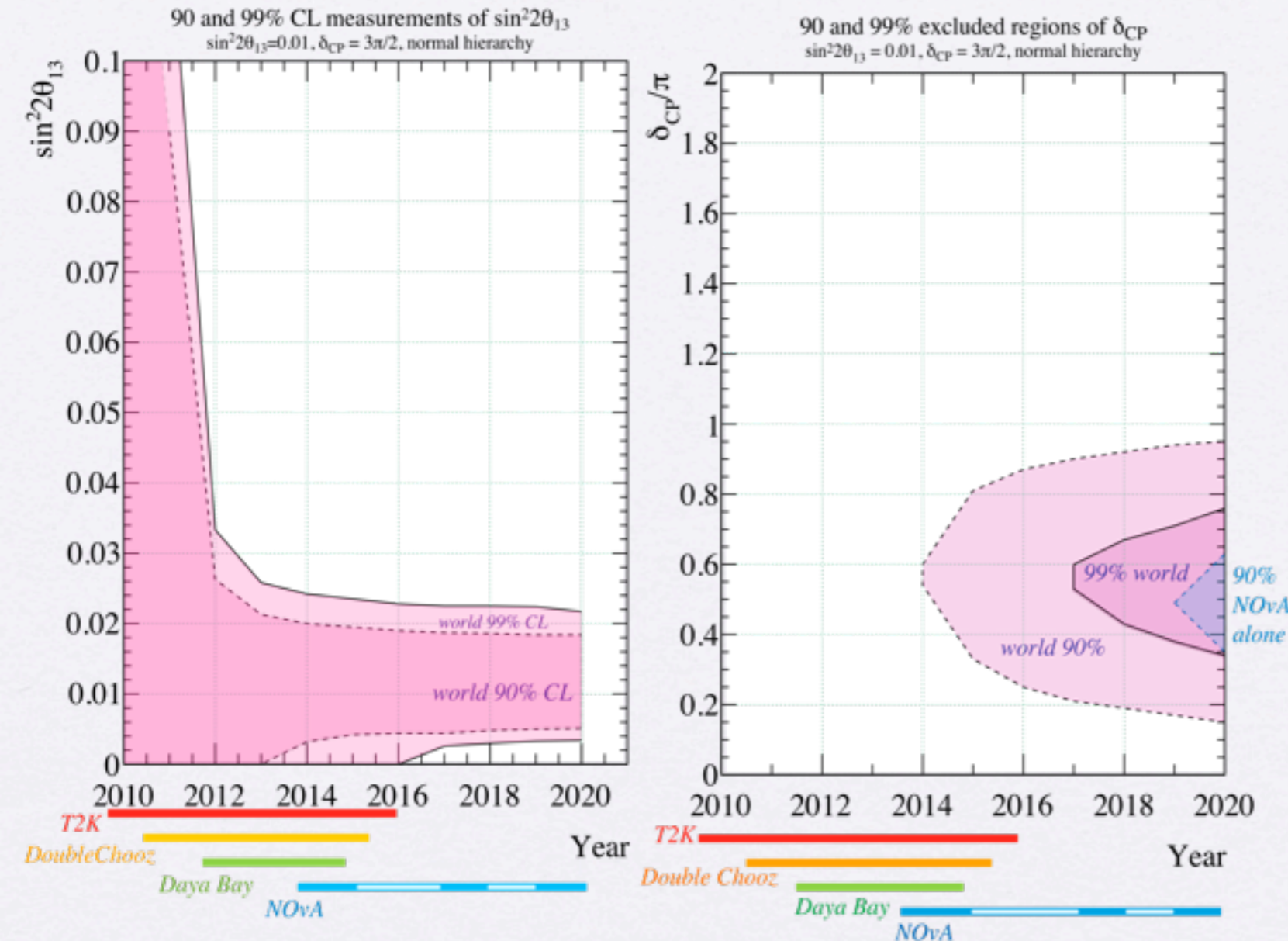


- NOvA can provide information about  $\delta_{CP}$  on its own.
- T2K+Daya Bay can contribute.
- All other experiments are combined for the world numbers.
- Just by starting NOvA you cover half the  $\delta_{CP}$  space.



# What if the mixing is small?

$$\sin^2 2\theta_{13} = 0.01$$



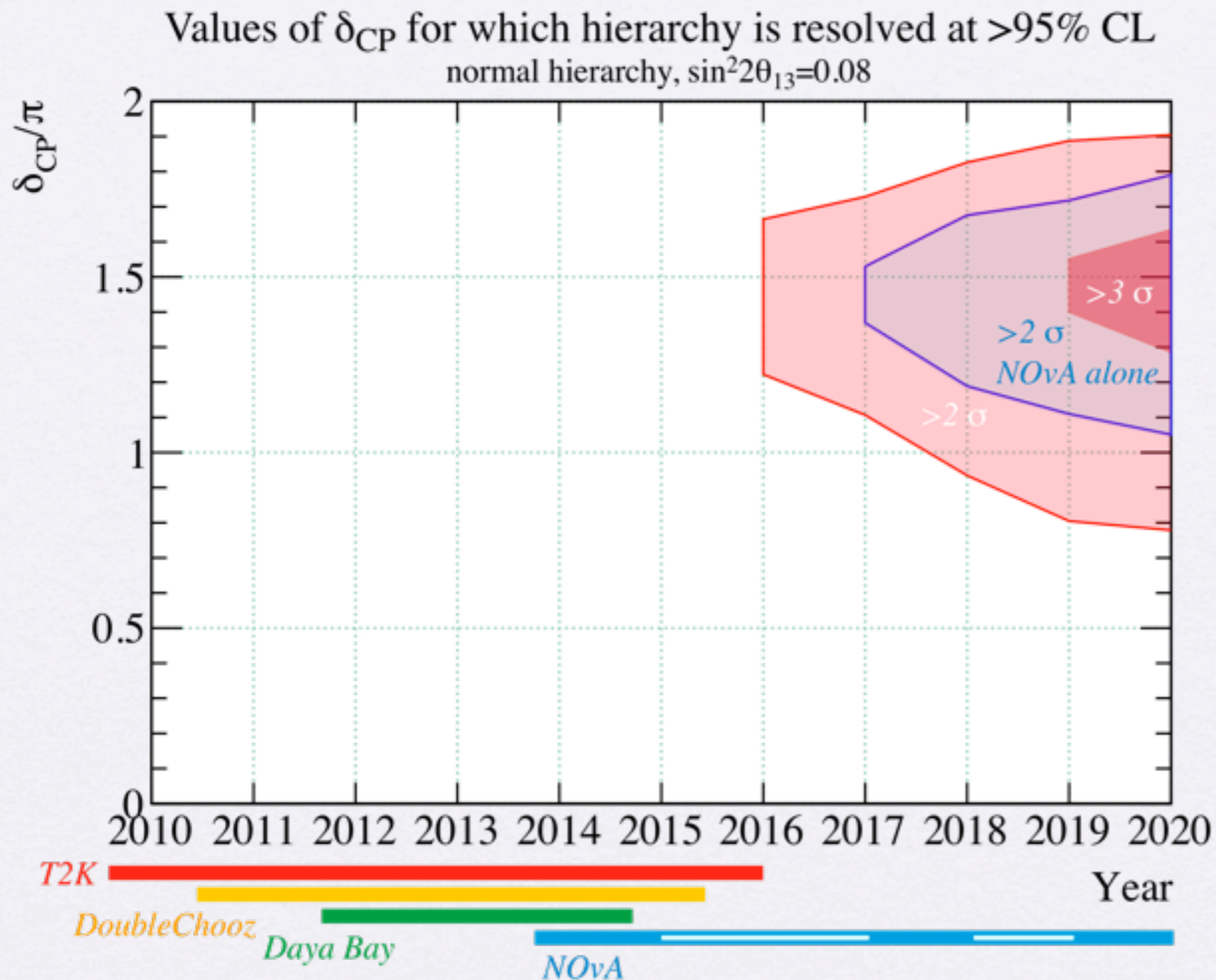
The addition of NOvA data pushes World limit on  $\sin^2 2\theta_{13}$  past 99% CL.

- NOvA can provide information about  $\delta_{CP}$  on its own.
  - T2K+Daya Bay can contribute.
- All other experiments need to be combined for the world numbers.
- Just by starting nova you cover half the  $\delta_{CP}$  space.



# Resolving the mass hierarchy

$$\sin^2 2\theta_{13} = 0.08$$



- NOvA can resolve the **mass hierarchy** on its own.
- T2K+Daya Bay +DChooz+NOvA create the larger exclusion.



# Far Detector site

Aerial view on August 25



- The whole building will be contracted.
- Accelerating procurement of materials:
  - PVC extrusions.
  - Wavelength-shifting fibers.
  - APDs.
  - Kicker parts.

Looking South  
Ash River, MN



# Far Detector site

Aerial view on August 25



Looking South  
Ash River, MN

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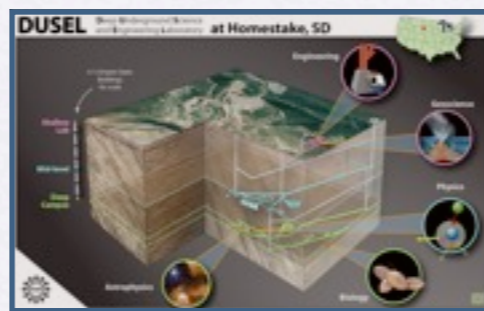
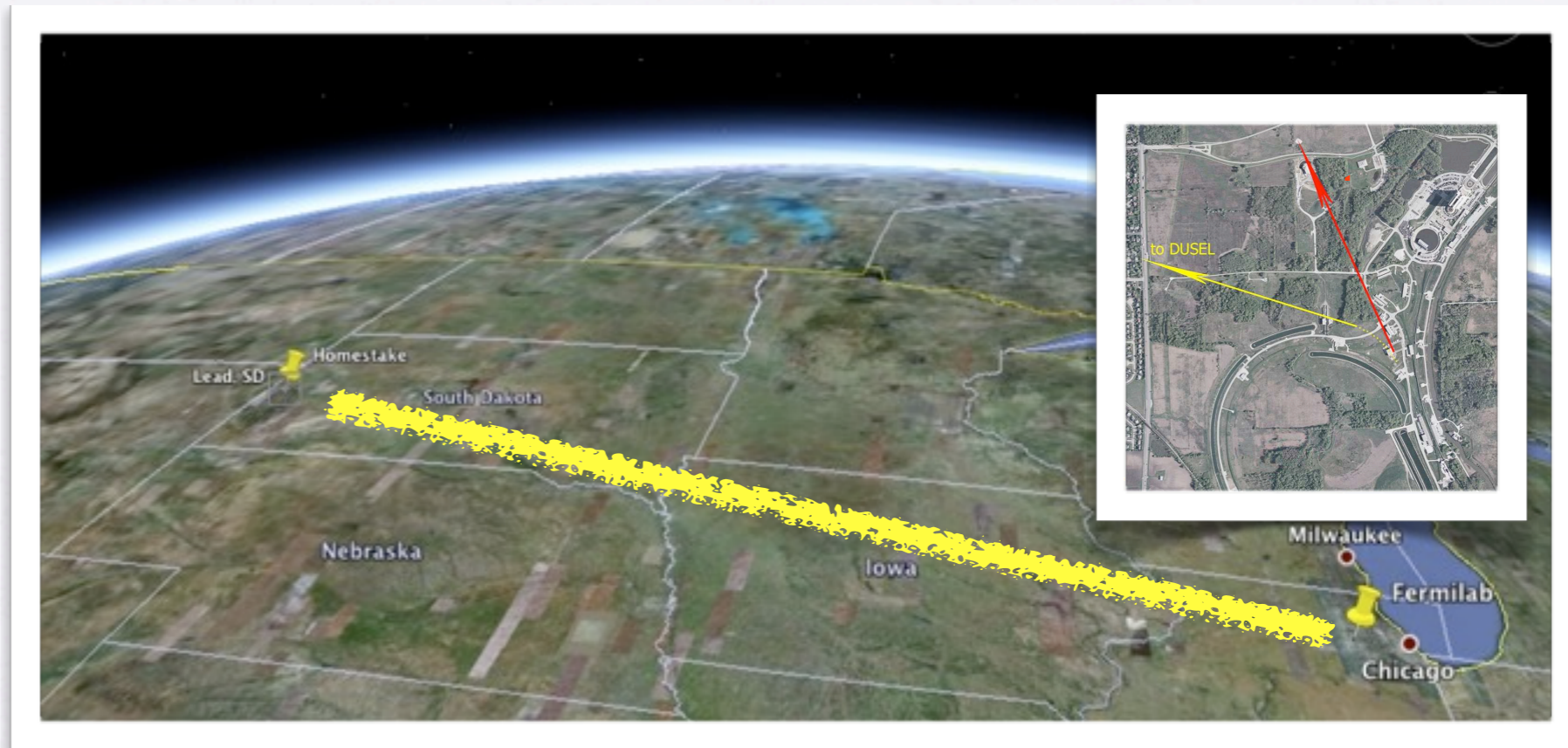
# NOvA role and prospects at ANL

- M. Sanchez: NOvA is offline software coordinator. Main goal is to get simulations and reconstruction ready for the IPND. Some analyses possible with these data.
- S. Budd: Beam simulations, in particular interface to the GENIE flux driver. Interface to MINOS beam monitoring and systematics.
- X. Huang: Simulations production and build new GEANT4 interface. Stopping muon calibration.
- Both postdocs will be involved in IPND commissioning and analysis of IPND data.

LBNE  
no logo

# LBNE in a nutshell

- Redirect and intensify your beam of neutrinos at Fermilab.
- Construct even bigger detector farther away this time on axis:
  - Default is 3 x 100 kton Water Cerenkov detectors.
- If neutrinos oscillate, electron neutrinos are observed at the Far Detector in Homestake, 1300 km away.



3rd generation  
← long baseline →



# LBNE Physics Reach

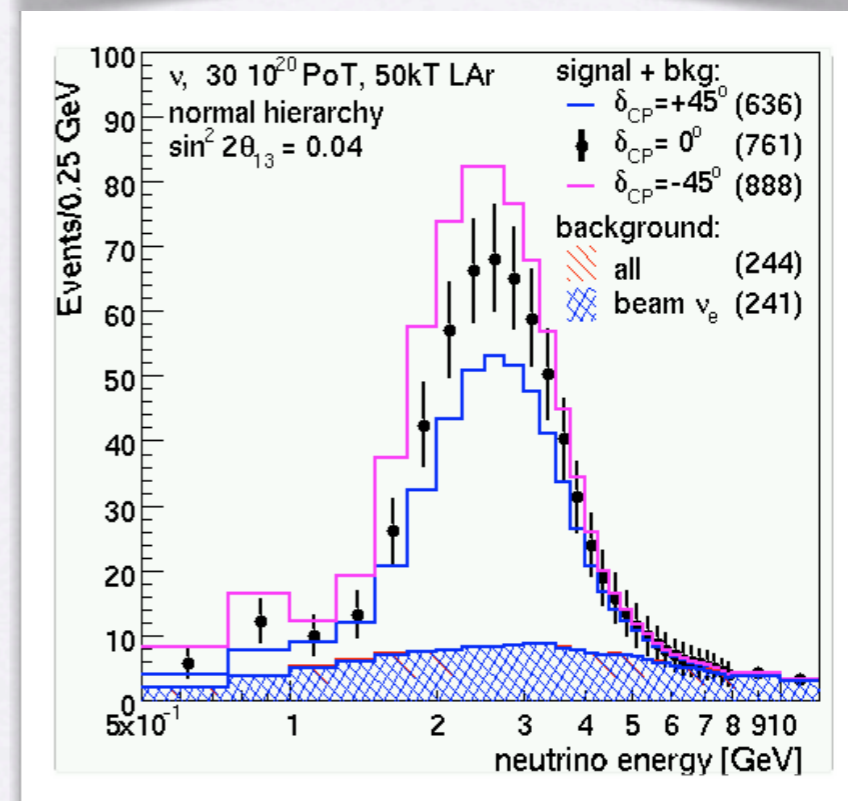
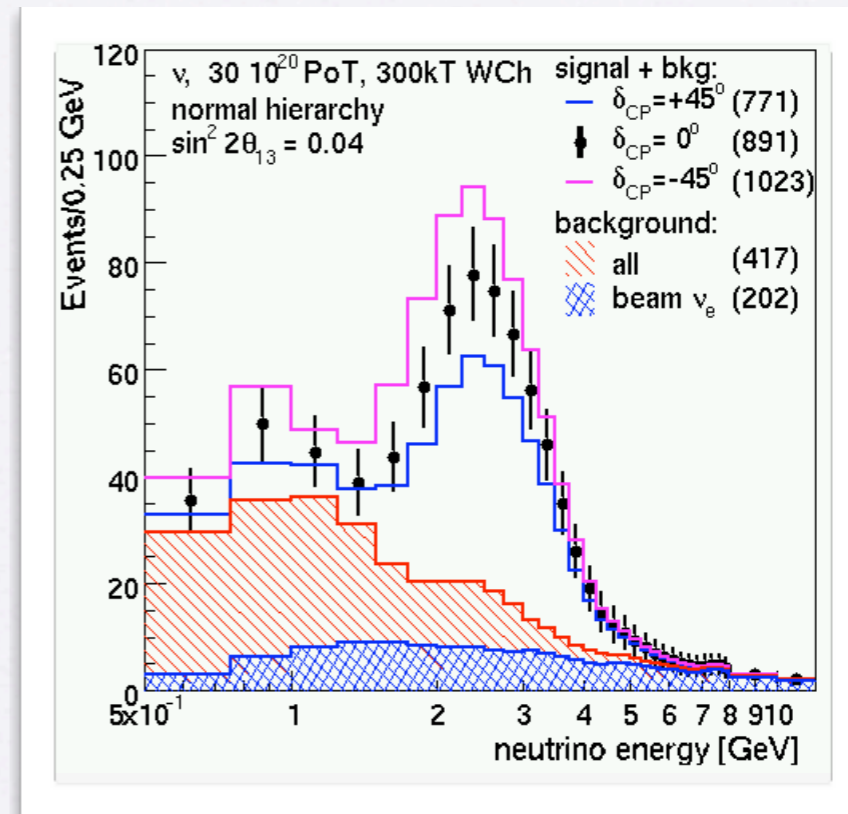
- Assuming:
  - 2.3 MW wide beam aimed at a 300 kton Water Cerenkov or a 50 kton Liquid Argon TPC,
  - 3 years of running for neutrino and 3 years for anti-neutrinos.

- For large  $\theta_{13}$ , measure:

$\sin^2 2\theta_{13}$  to  $\sim 5\%$  and  $\delta_{cp}$  to  $\sim 15^\circ$

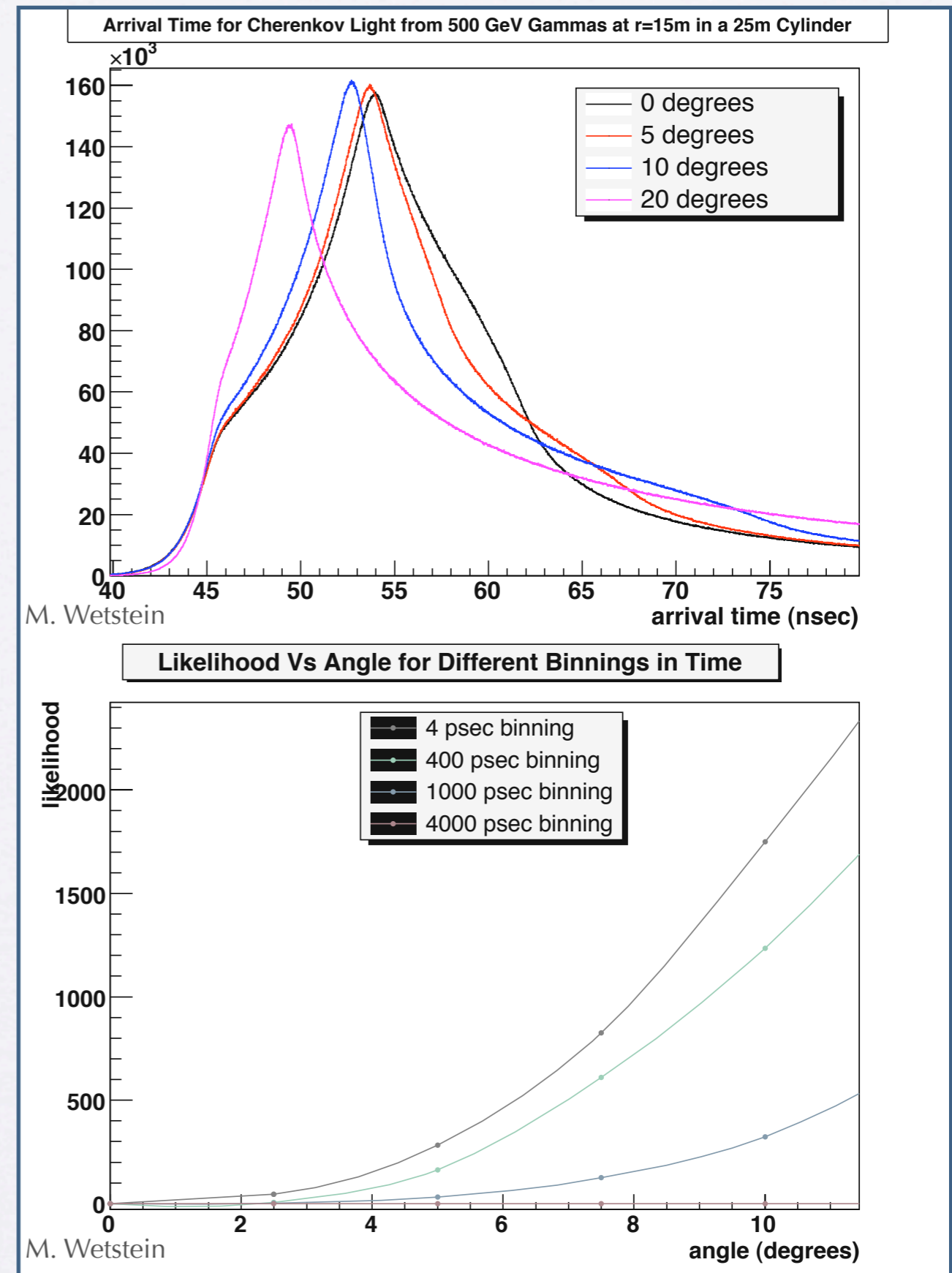
- Sensitivities at 3 sigma:

	$\sin^2 2\theta_{13} >$	
$\sin^2 2\theta_{13} \neq 0$	0.004	(all $\delta_{cp}$ )
$\text{sign}(\Delta m_{31}^2)$	0.014	(all $\delta_{cp}$ )
CP violation	0.012	(50% $\delta_{cp}$ )



# Large-Area Fast Photosensors for LBNE

- Main interest to explore new approaches to Water Cerenkov.
- Goal is to improve background rejection and vertex resolution using large-area/fast timing photosensors being designed at ANL.
- Contributing to the development of the Water Cerenkov simulations as they are being worked on.



# LBNE prospects and plans at ANL

- M. Sanchez: Helping establish computing infrastructure. Member of NuComp.
- M. Wetstein, M. Sanchez:
  - Joined the LBNE Water Cerenkov simulation group.
  - Developing toy MC to test parameter space of design parameters and select best avenues for improvement.
  - Initial goal is to provide feedback to hardware design group.
- Effort needs to grow in FTE. Collaborating with UCDavis/UChicago.

# Summary

- ANL's continuing effort in searching for electron neutrino appearance within the US long baseline neutrino program:
  - MINOS continue to contribute to the  $\nu_e$  appearance analysis.
  - NOvA prepare all the tools for the IPND data analysis. Participate in the commissioning of the IPND. Analyze data.
  - LBNE contribute to the simulations work. Study application of new photosensors to improve physics in the Water Cerenkov detector.

Backup slides

# MINOS recent results

study “atmospheric” neutrino oscillation parameters

✓ Study  $\nu_\mu$  disappearance as a function of energy:

✓ Precision measurements of  $\Delta m^2_{32}$  and  $\sin^2(2\theta_{23})$ .

$$|\Delta m^2_{32}| = 2.43 \pm 0.13 \times 10^{-3} \text{ eV}^2 \text{ (68\% CL)}$$
$$\sin^2 2\theta_{23} > 0.90 \text{ (90\% CL)}$$
$$\chi^2/\text{ndf} = 90/97$$

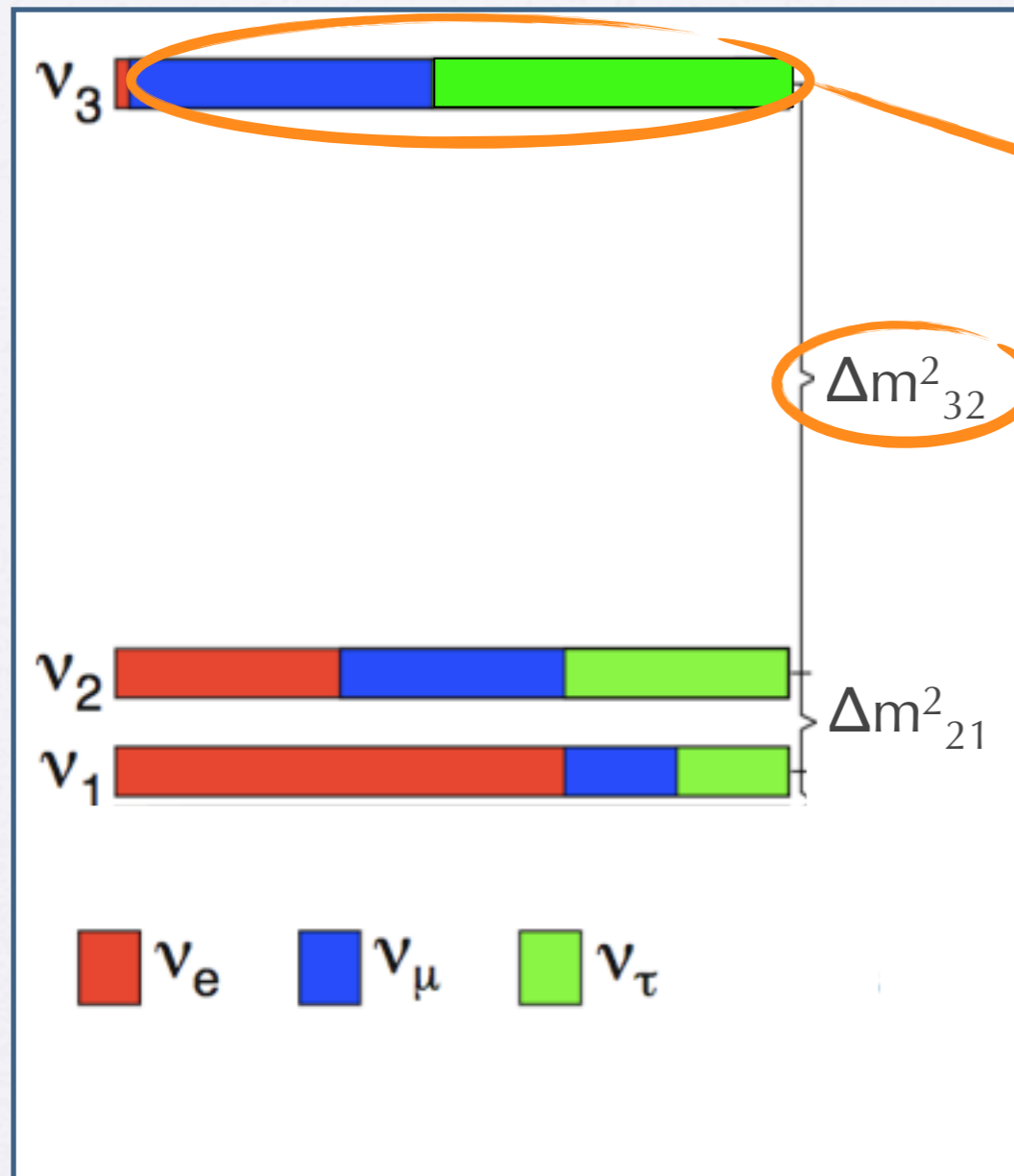
✓ Mixing to sterile neutrinos at  $\Delta m^2_{34} \sim \Delta m^2_{32}$ :

✓ Fraction of neutrinos that oscillate into the sterile state.

Assuming no electron neutrino appearance:

$$f_s = 0.28^{+0.25}_{-0.28} \text{ (stat.+syst.)}$$

$$f_s < 0.68 \text{ (90\% CL)}$$



PRL **101** 131802 (2008)

PRL **101** 221804 (2008)

Mayly Sanchez - ANL/ISU

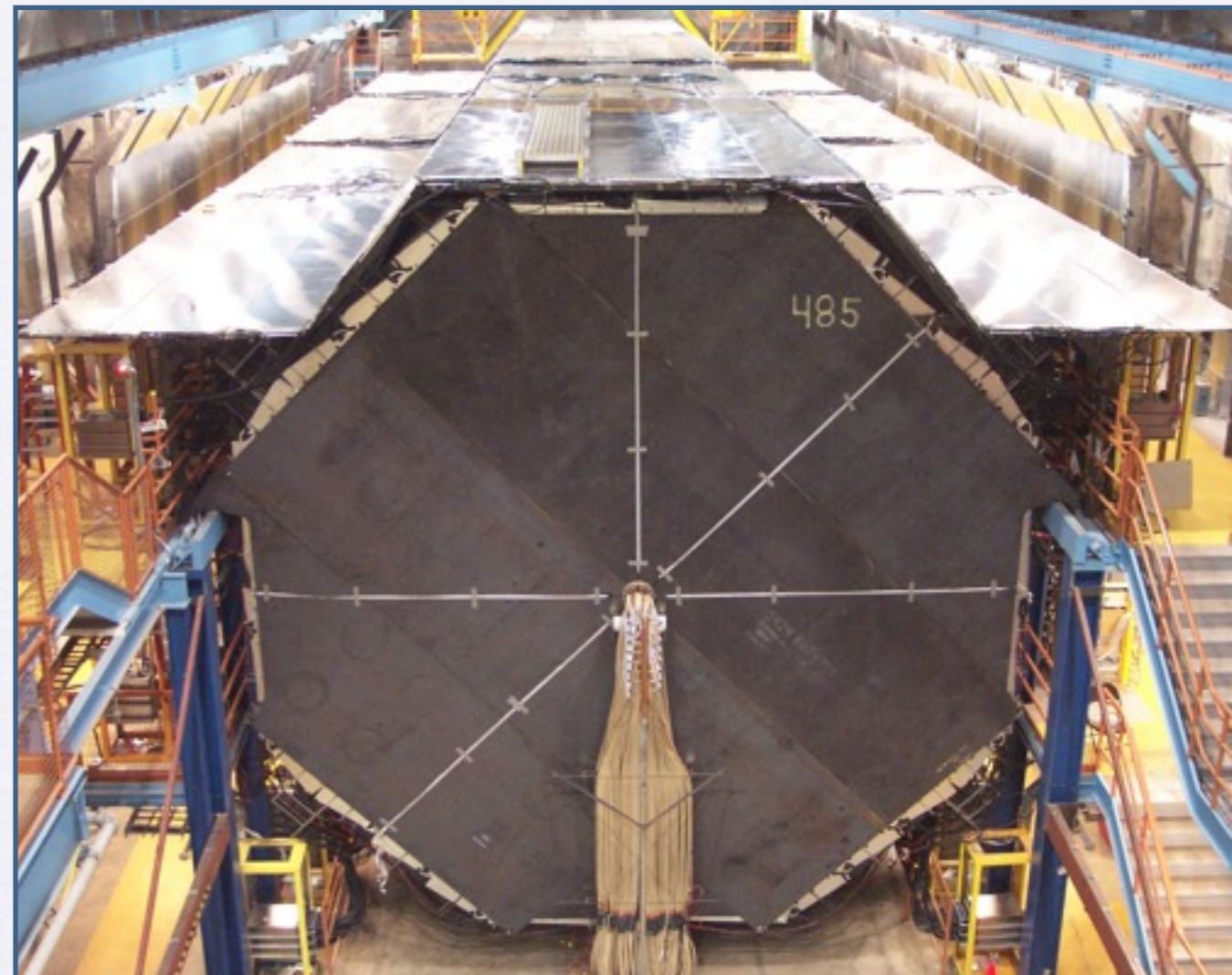


# The MINOS detectors

- To first order functionally identical: Near and Far detectors
- 1 inch thick octagonal steel planes, alternating with planes of 4.1 cm x 1 cm scintillator strips, up to 8m long.
  - Near: ~ 1kton, 283 steel squashed octagons. Partially instrumented. 153 scintillator planes. Requires faster readout.
  - Far: 5.4 kton, 486 (8m/octagon) fully instrumented planes.



Mayly Sanchez - ANL/ISU

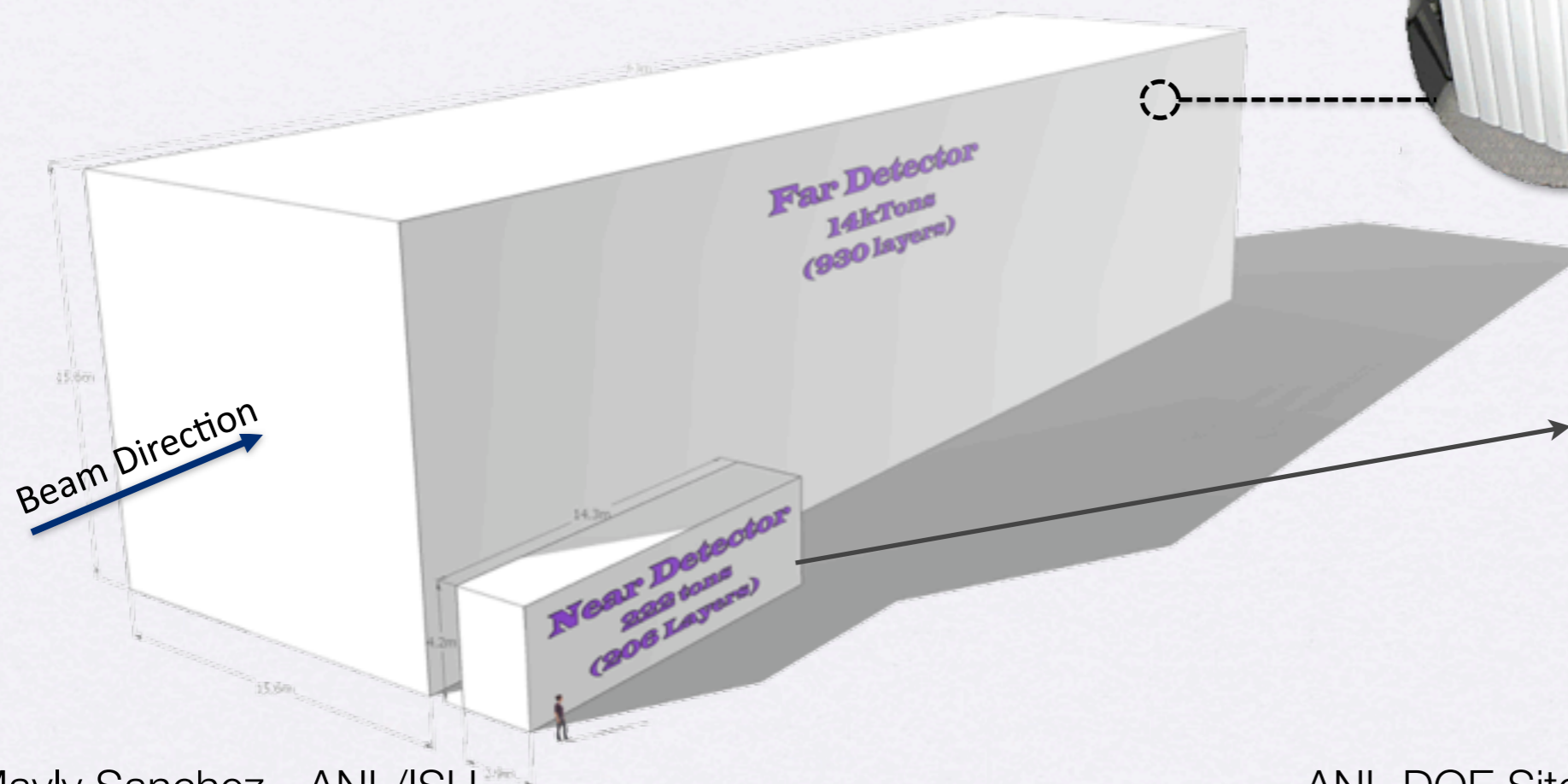


ANL DOE Site Visit - Sept. 23-24, 2009



# The NOvA Detectors

- 14 kton Detector ( $\sim 3\times$  MINOS).
- $>70\%$  active detector.
- Plastic cells filled with scintillating mineral oil.
- Each plane just  $0.15 X_0$ . Great for electrons (in MINOS  $1.44 X_0$ ).
- Cells are  $3.9 \times 6.0$  cm.
- $15.6 \times 15.6 \times 68$  m for Far.
- $4.2 \times 2.9 \times 15.3$  m for Near.

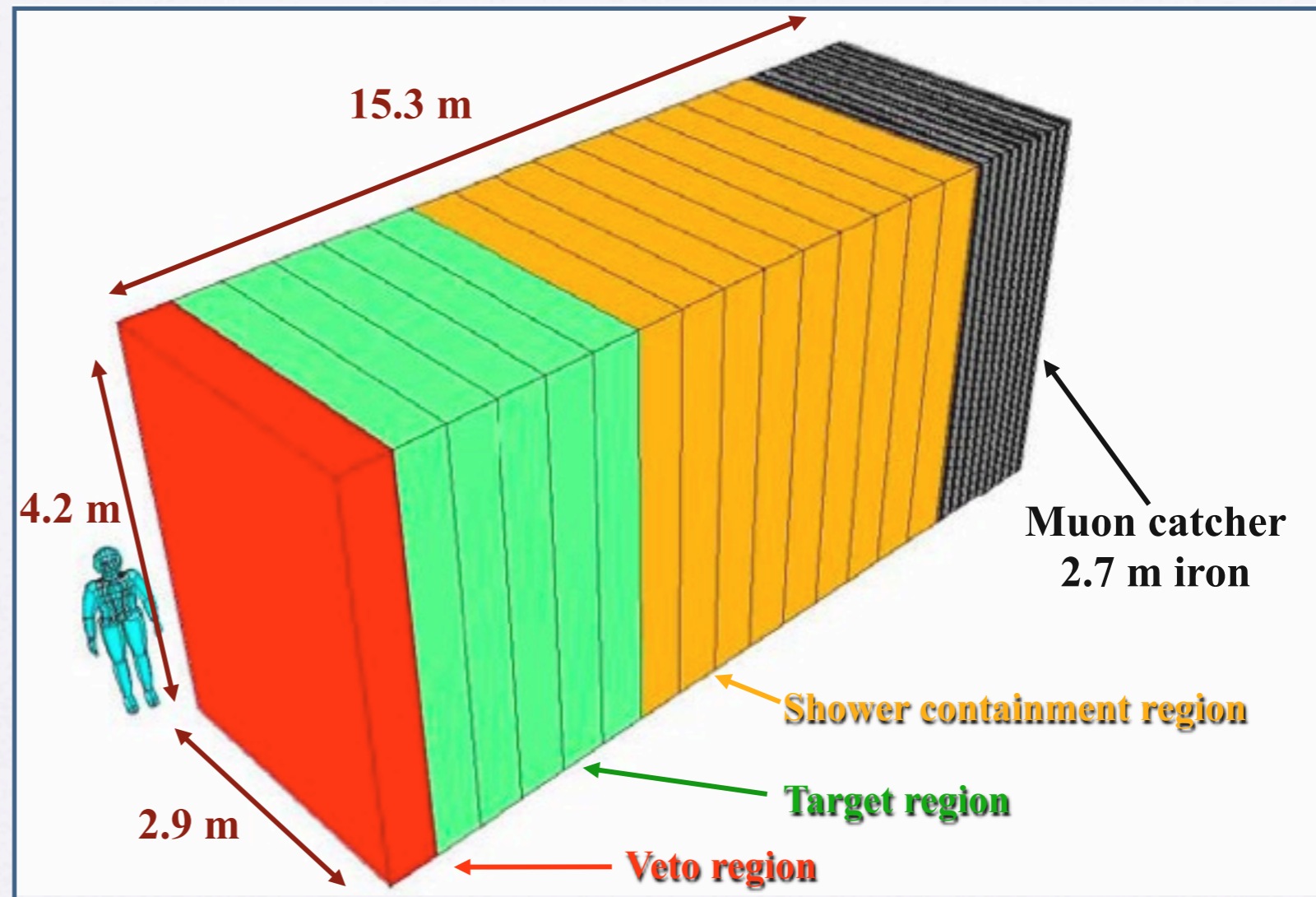


Now also starring as the IPND. To be placed on the surface before going underground at the Fermilab site.



# The Near Detector and the Integration Prototype Near Detector

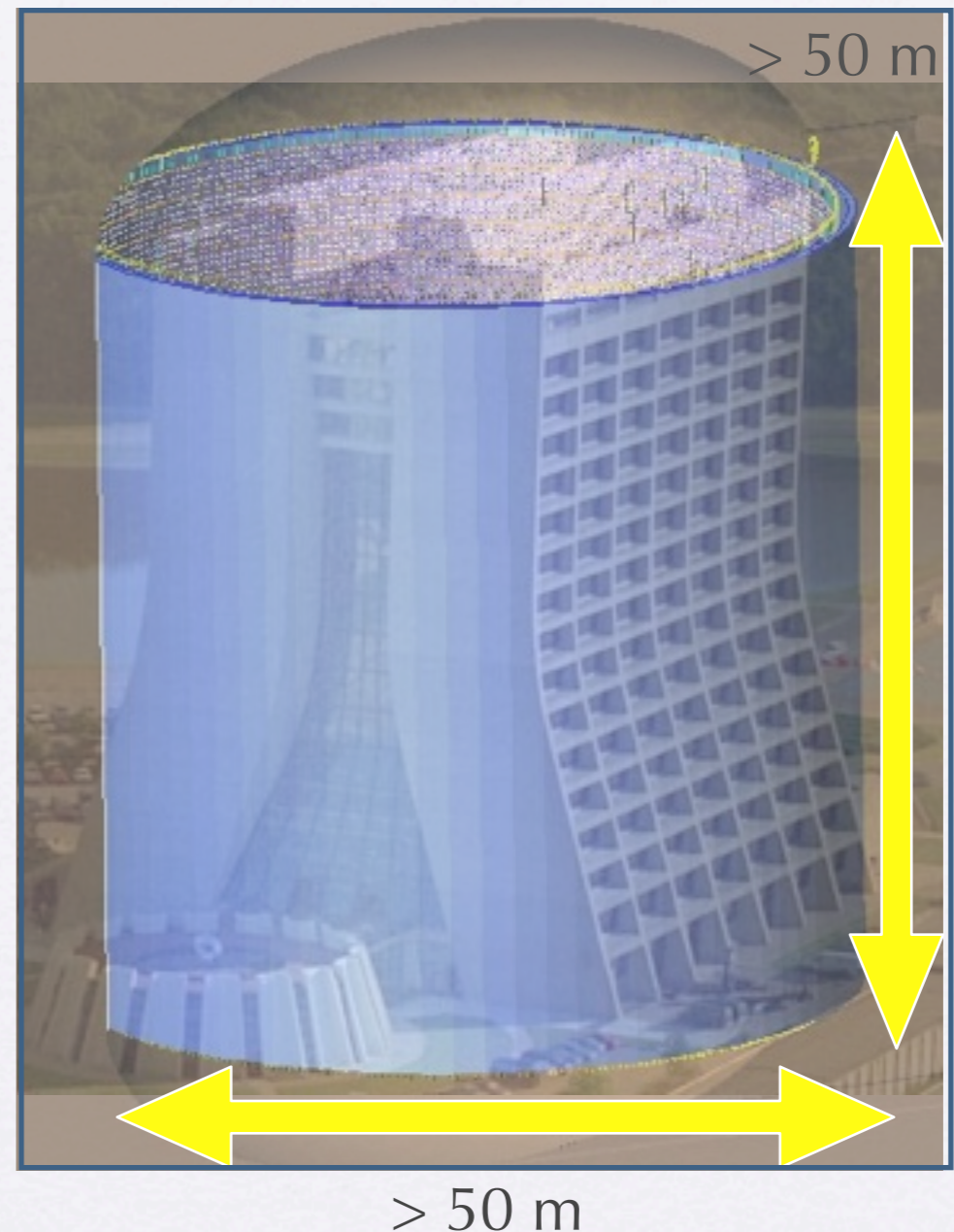
- Test running with the Near Detector placed on the surface outside of the MINOS building.
- Start taking data Spring 2010.
- By the Fall 2011, it will be moved into the MINOS access tunnel for physics data-taking at 14 mrad just like the Far Detector.



222 tons total mass  
125 tons active volume  
23 tons fiducial volumen

# Proposed detector technology

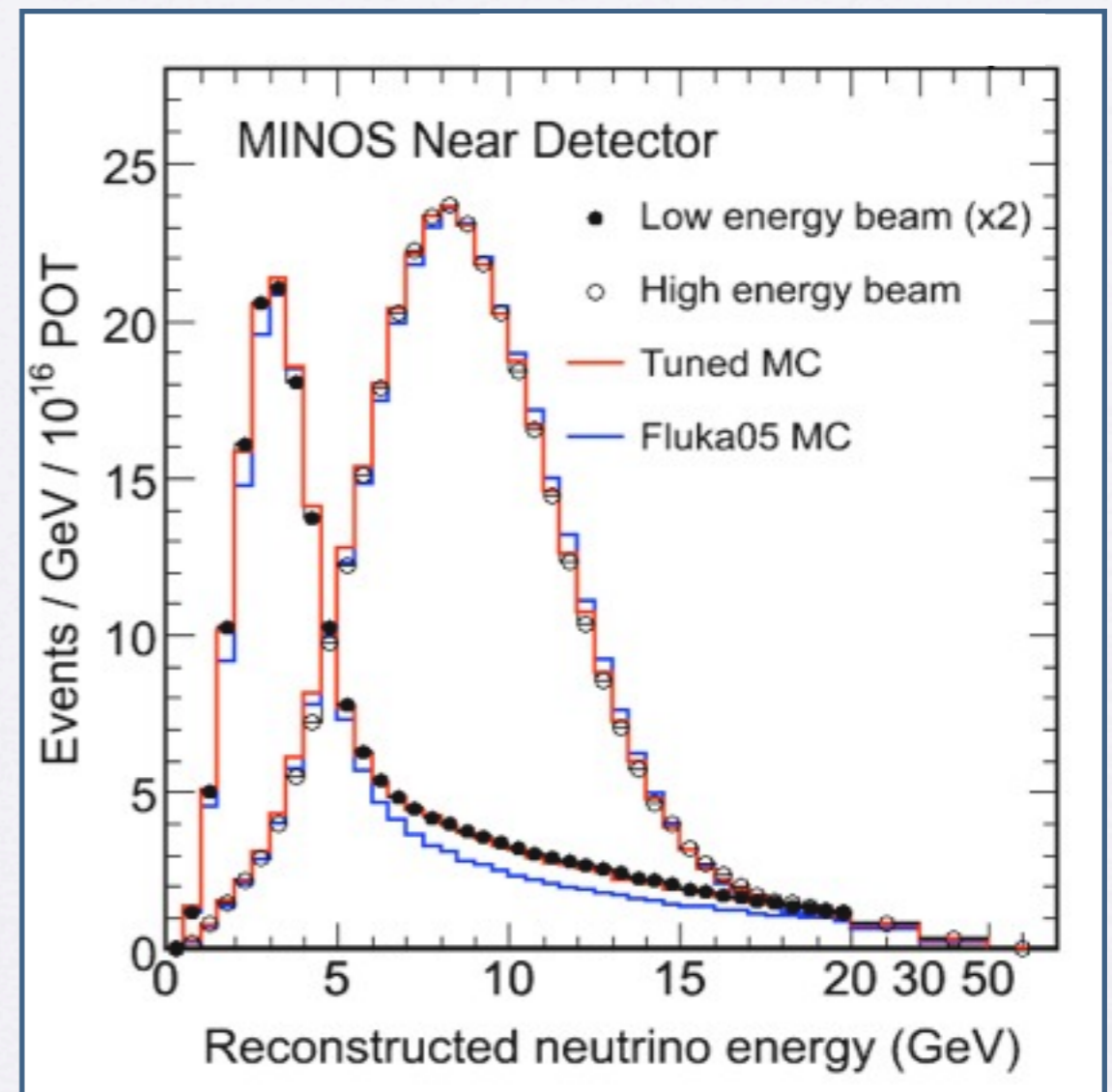
- Baseline is Water Cerenkov detector.
- Initial detector 300 kton in 3 modules of 100 kton fiducial each.
- Cylinder of 50-60 m in diameter and height.
- Depth 4200 mwe.
- PMT coverage 25%, 10-12 inch PMT.
- Cost ~115 M/module



# The NuMI Beam

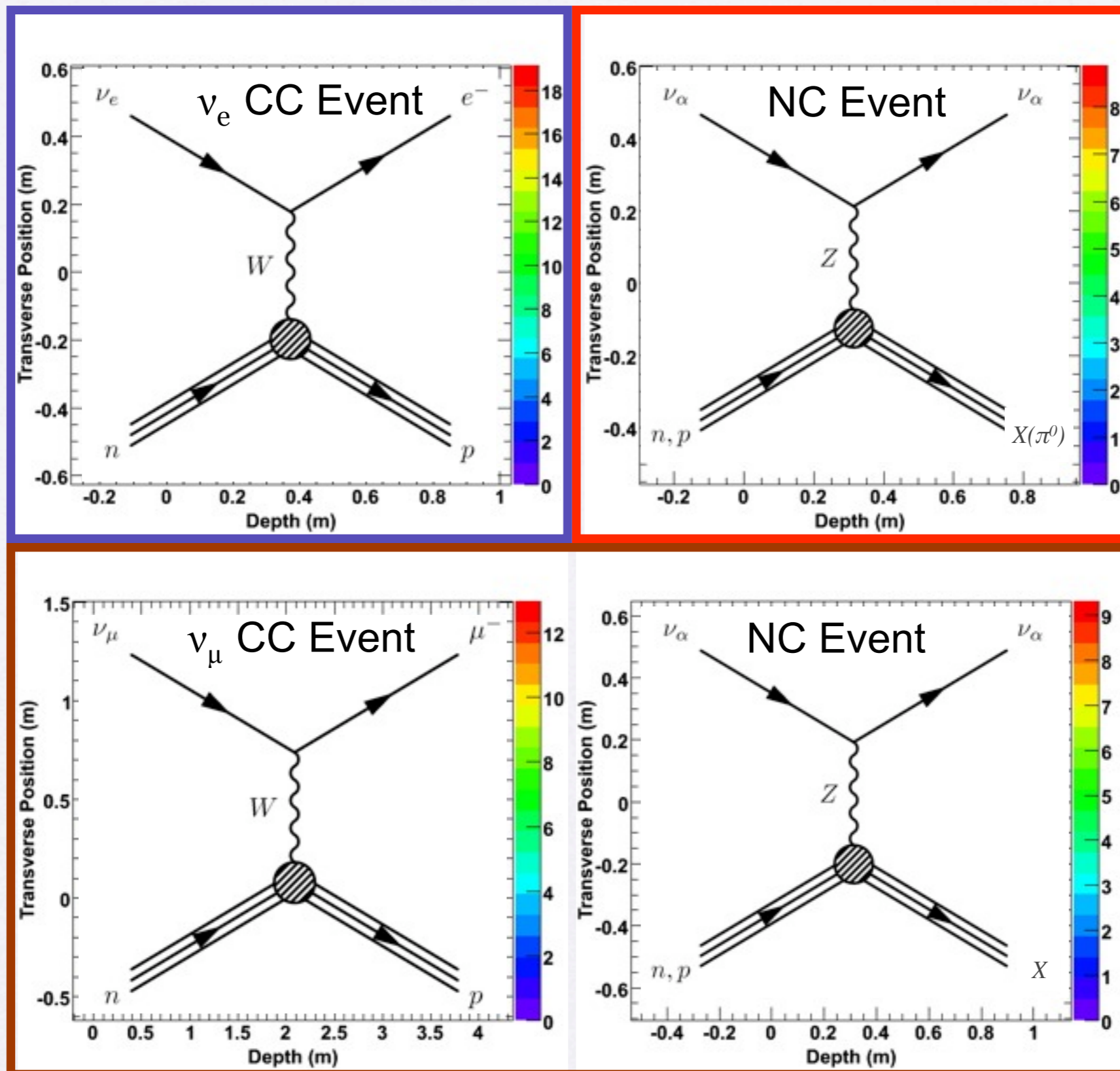
- NuMI is primarily a  $\nu_\mu$  beam.
  - 1.3% of  $\nu_e$  contamination from pion and kaon decays.
- Neutrino spectrum changes with target position with respect to focusing horns.
  - We use  $\nu_\mu$  CC events in ND to constrain flux.
- Region of interest dominated by events from secondary muon decays,
  - Constrained by  $\nu_\mu$  CC spectra.
- Uncertainties on the beam  $\nu_e$  flux in the region of interest are  $\sim 10\%$ .

## NeUtrinos from the Main Injector



Measured  $\nu_\mu$  CC events

# Neutrino Event Topologies

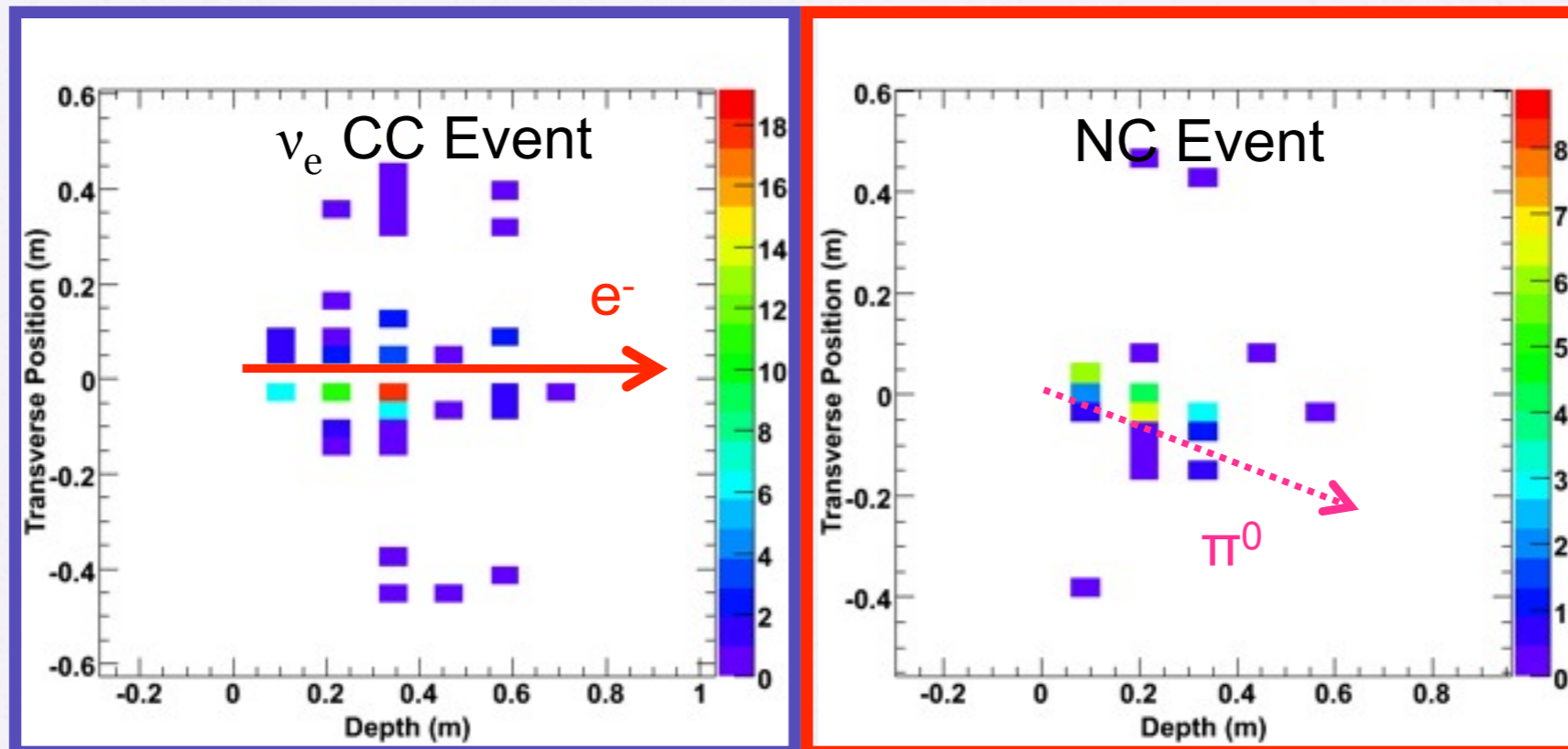


# Neutrino Event Topologies

To select  $\nu_e$  CC we focus on finding compact showers.

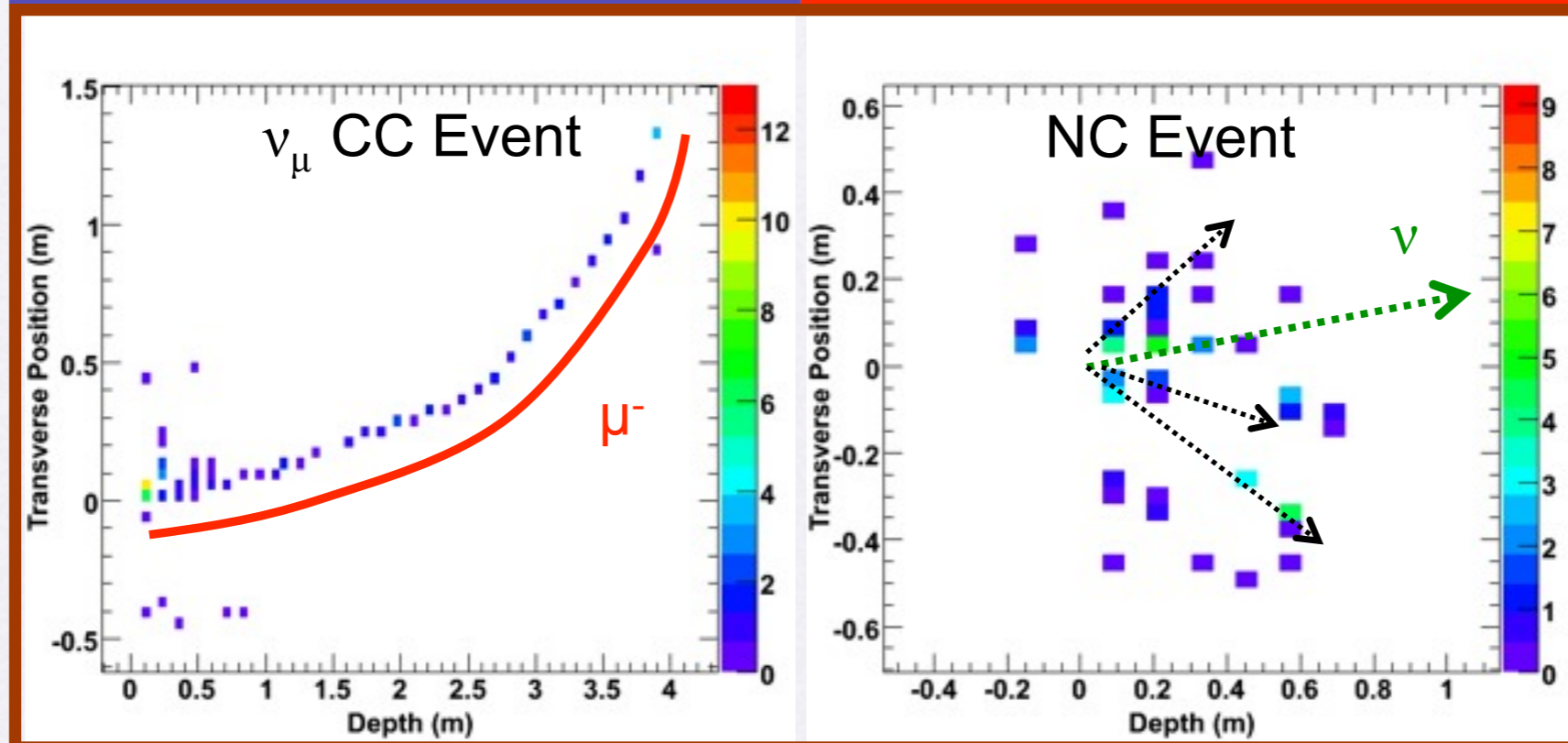
MC events

Signal



“Irreducible”  
Background

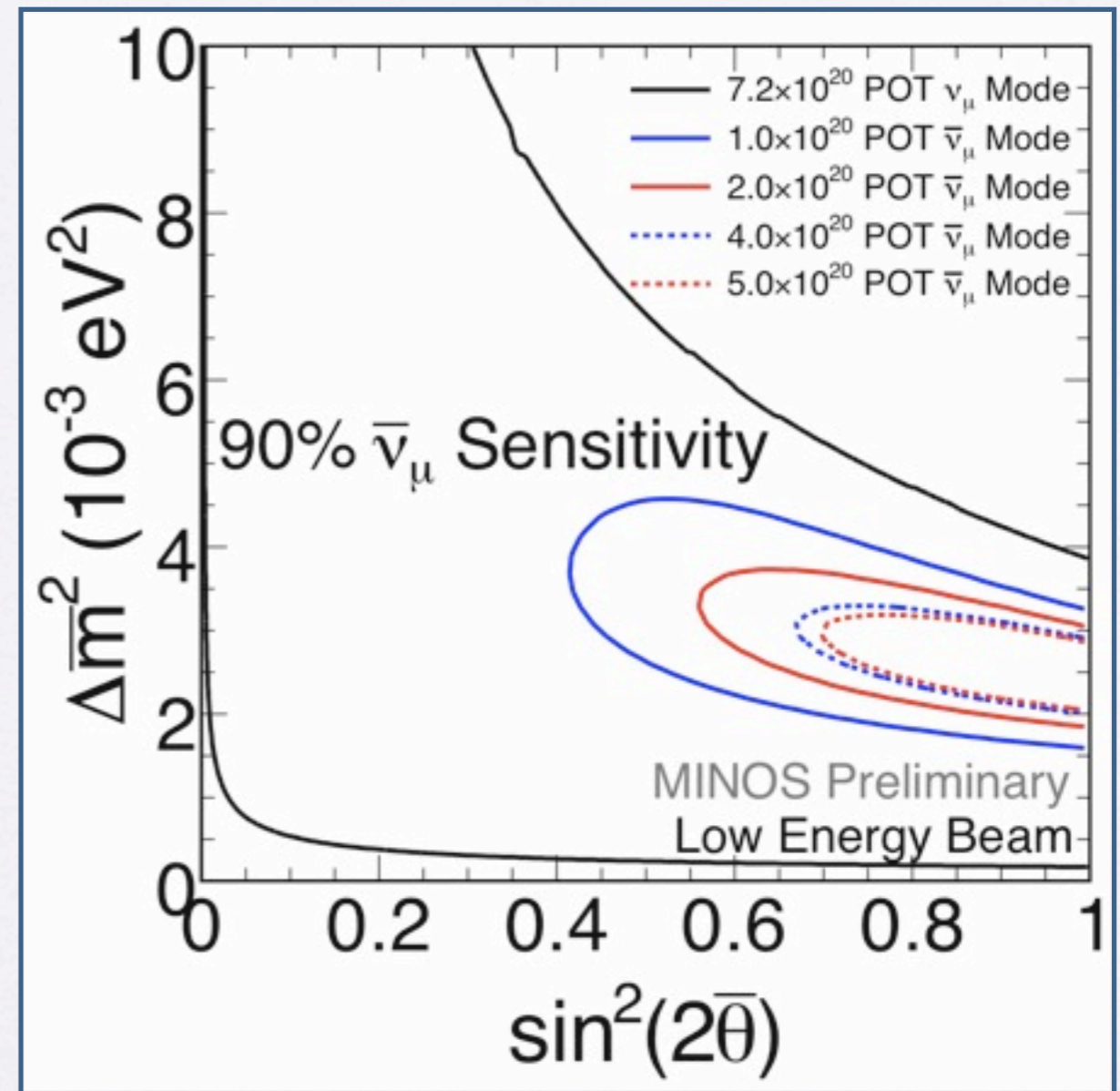
Reducible  
Background





# $\bar{\nu}_\mu$ disappearance in MINOS

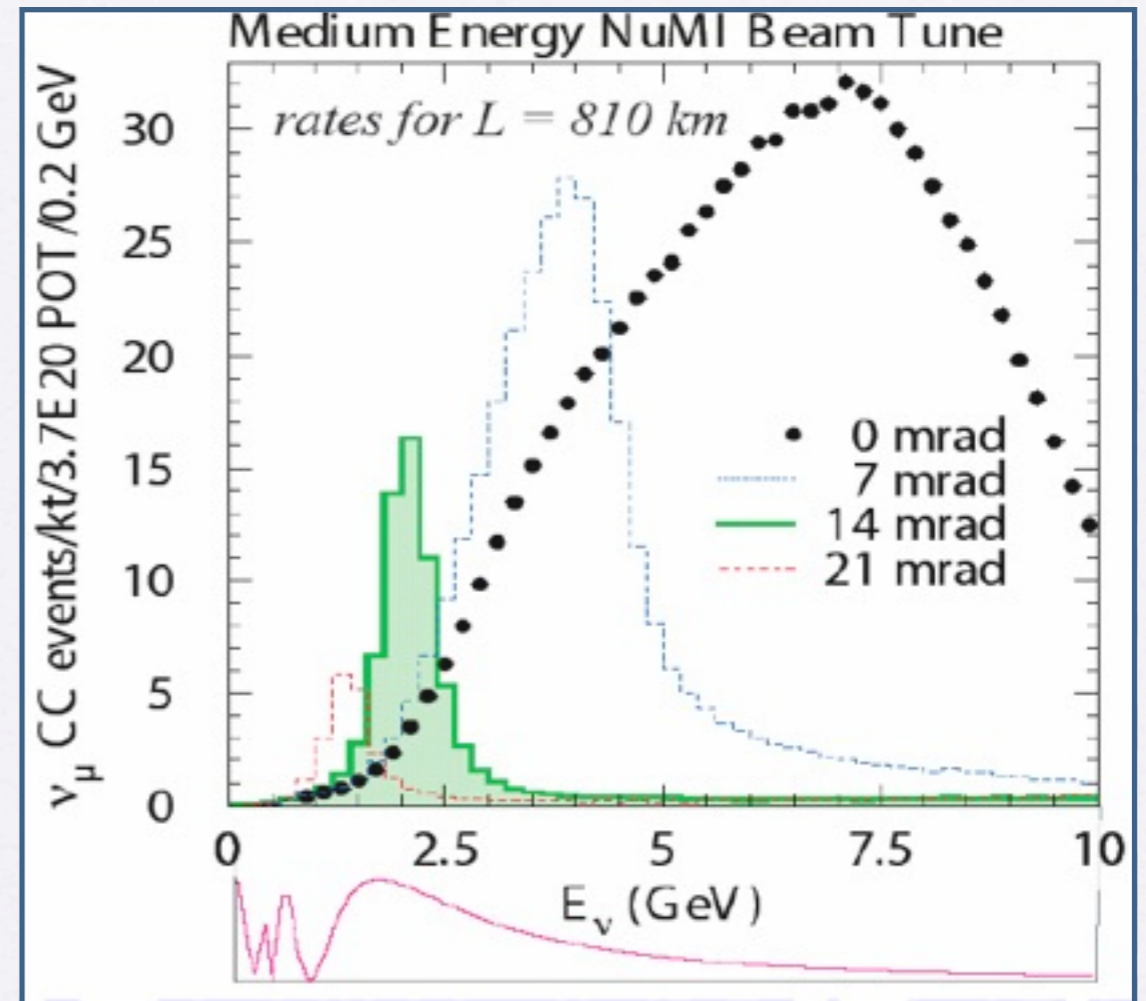
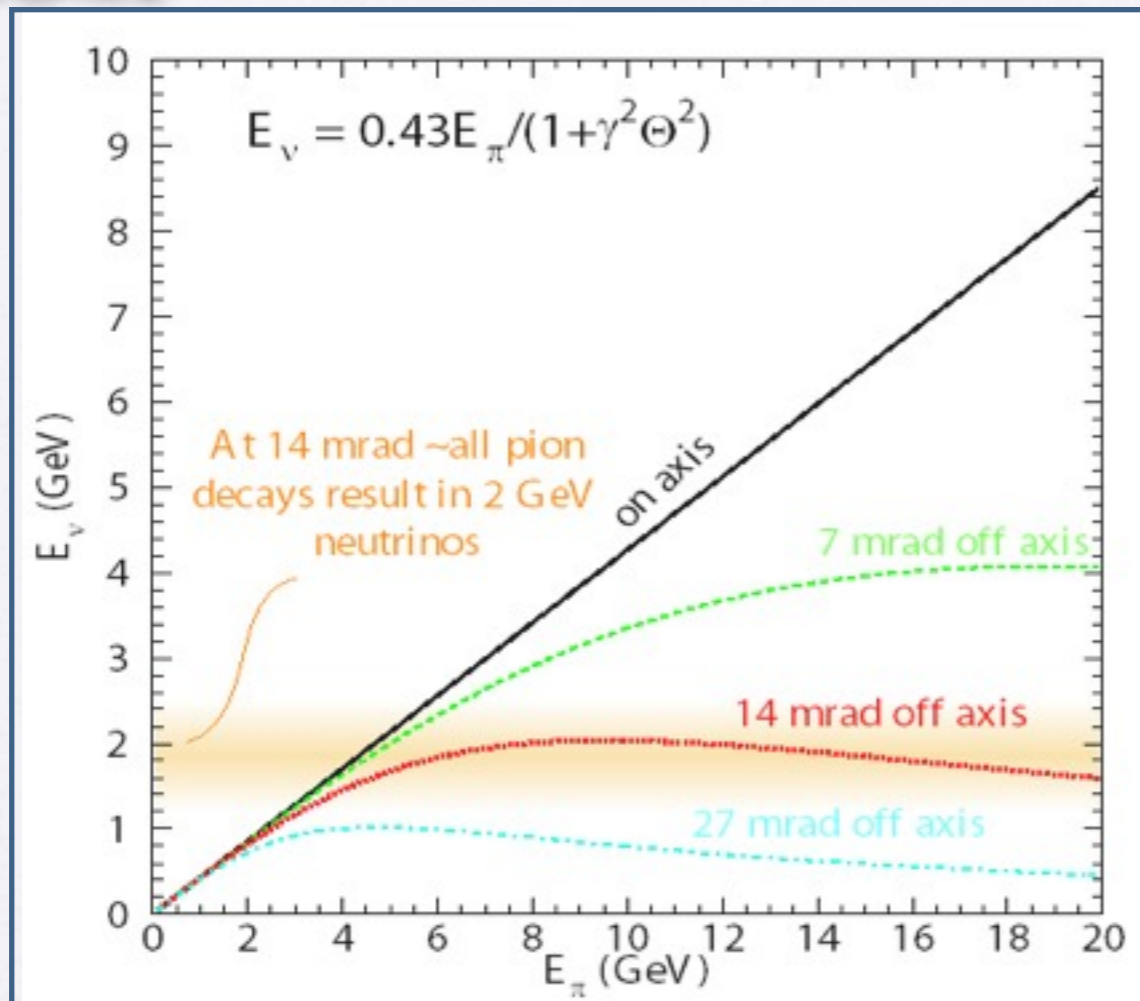
- Plan to reverse horn current in NuMI magnetic horns from Sept '09.
- MINOS can directly observe  $\bar{\nu}_\mu$  disappearance at the  $7\sigma$  level with  $5 \times 10^{20}$  POT.



◆ First direct observation of  $\bar{\nu}_\mu$  in an accelerator long baseline experiment.



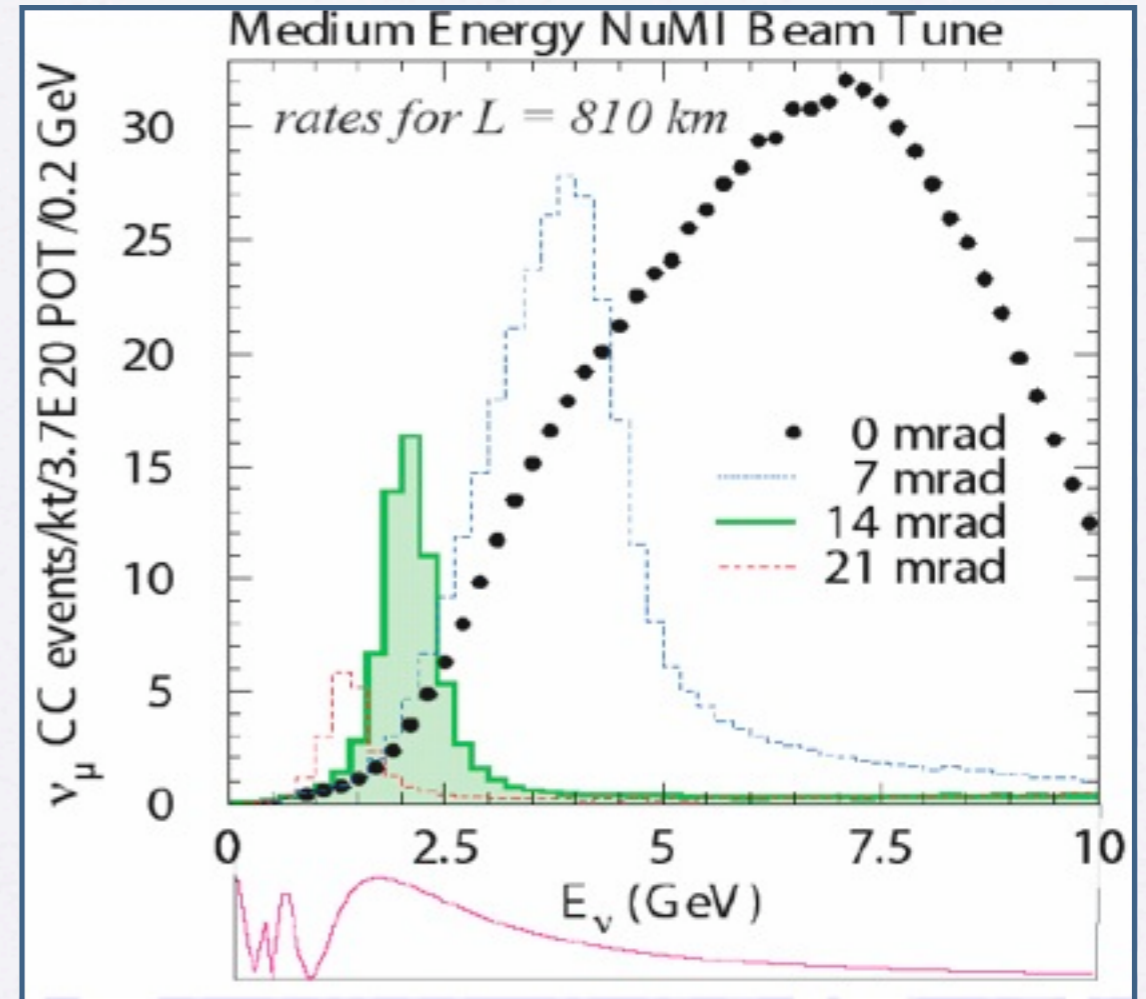
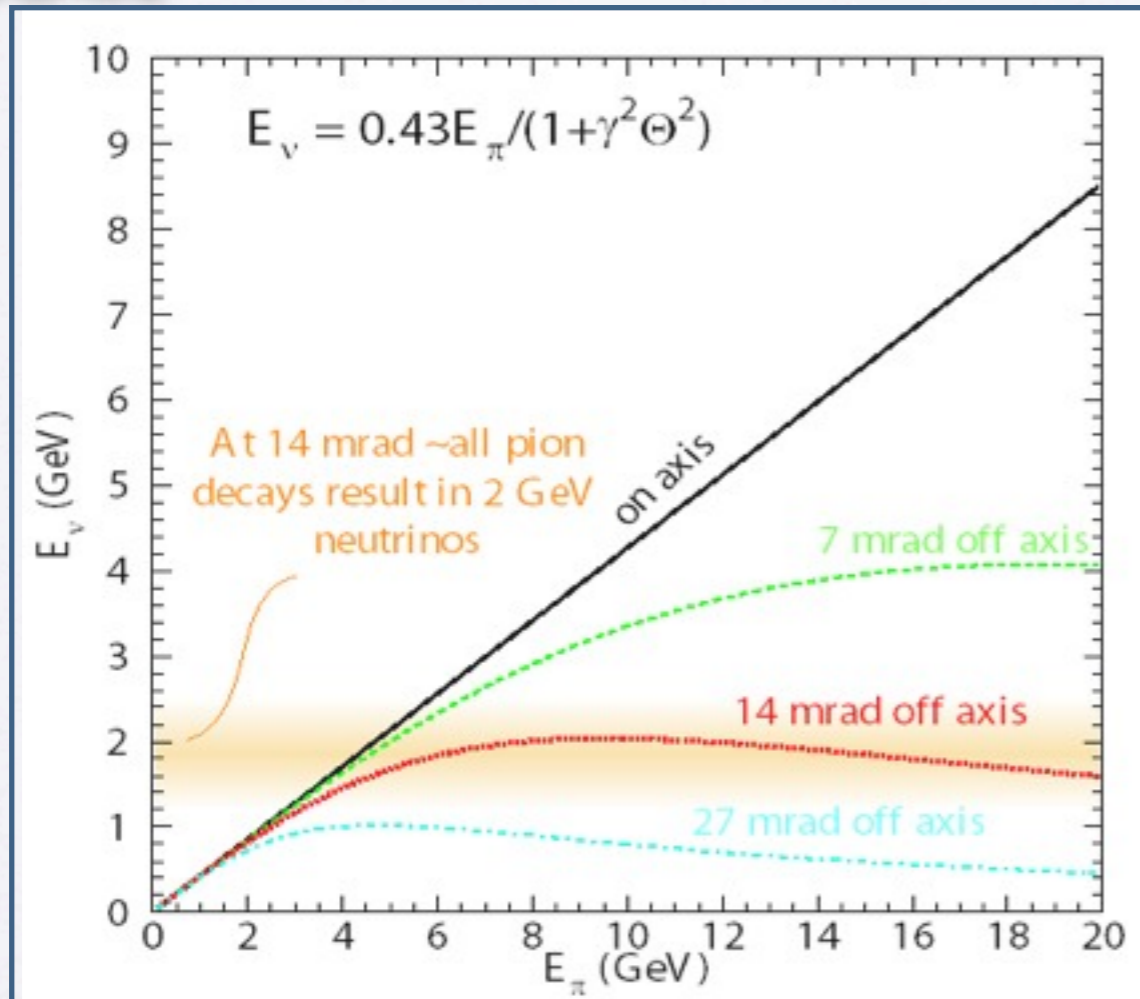
# Off-axis NuMI Beam



- Off-axis yields a narrow band beam. Peak sits just above oscillation maximum with 5 times the flux than on axis. High energy tail is suppressed.
- Upgrade neutrino beam intensity from 320kW to 700kW:
  - Use the recycler ring to store 12 batches while Main Injector ramps up.
  - Rate of Main Injector increases cycle time from 2.2 sec to 1.33 sec.



# Off-axis NuMI Beam



- Beam performance:
  - 10  $\mu$ sec spill every 1.3 sec.
  - $4.9 \times 10^{13}$  POT/spill.
  - $\sim 3 \times 10^{18}$  POT/day  $\rightarrow 6 \times 10^{20}$  POT/yr.
  - Running plan is 3 yrs  $\nu_\mu$  and 3 yrs  $\bar{\nu}_\mu$ .

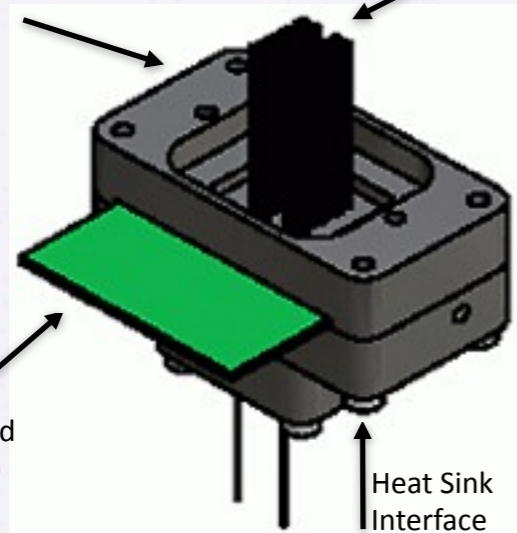


# Detector Elements

APD Module

"Clam Shell"  
Optical Housing

Carrier Board  
w/ APD chip



64 fiber  
bundle

- There are 11,160 detector modules for a total of 357,120 separated detector cells in the NOvA Far Detector.
- Each module is made of two high reflectivity PVC extrusions. Combined 12 module wide X or Y measuring planes.
- 12,500 km of 0.7 mm fiber, 3 M gallons of scintillator.

To APD Readout

Scintillation Light

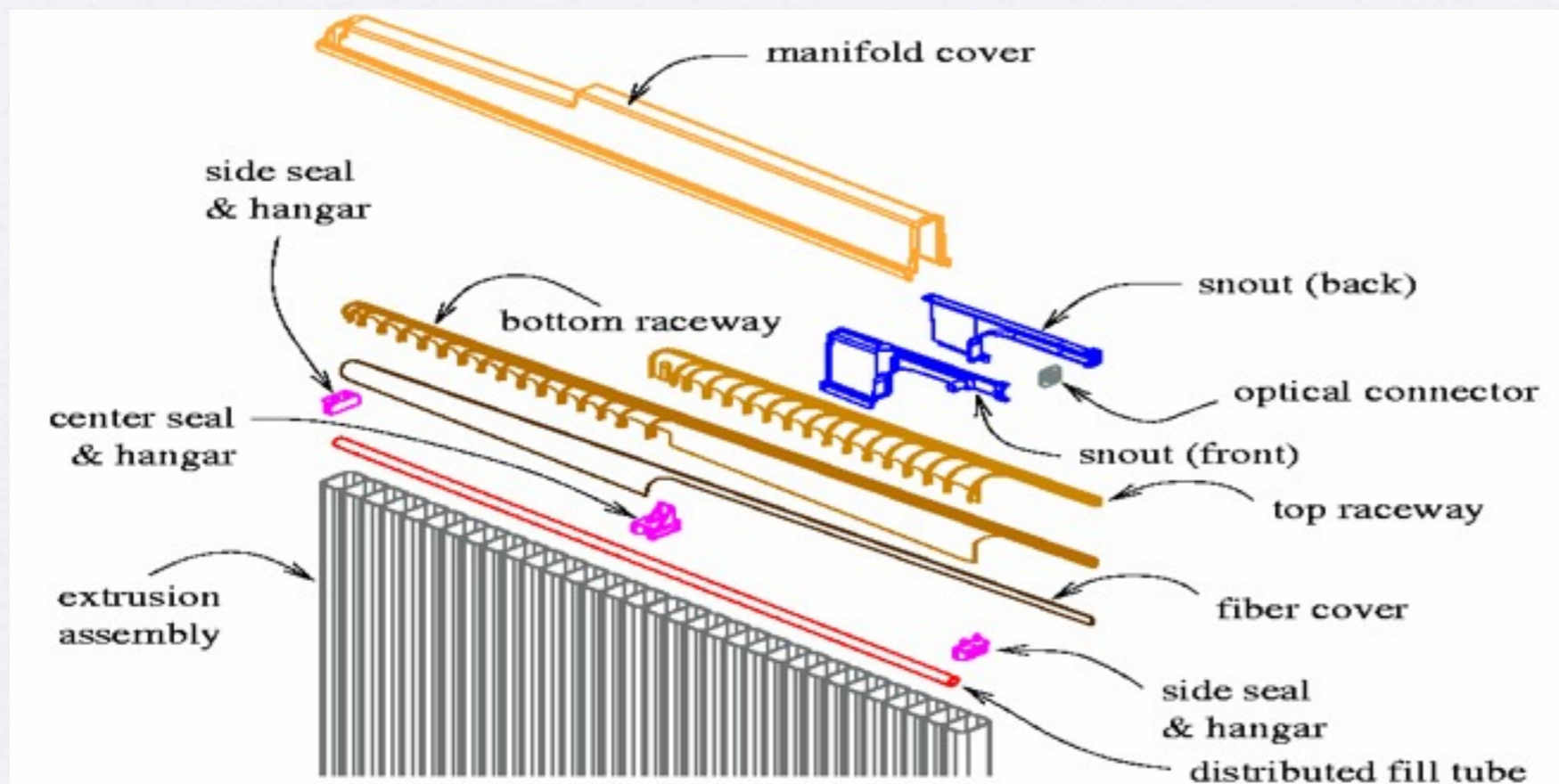
Particle Trajectory

Waveshifting  
Fiber Loop

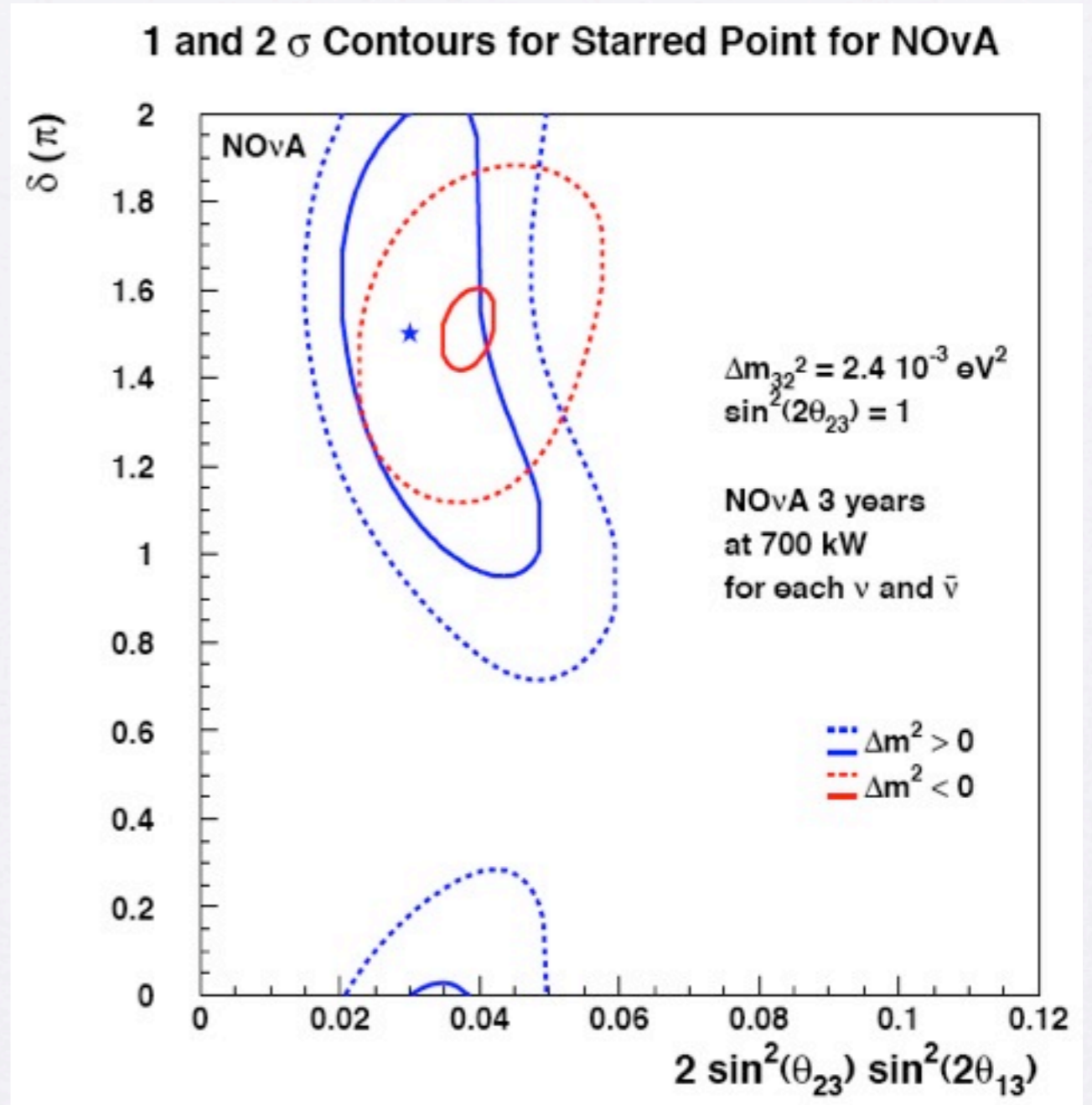
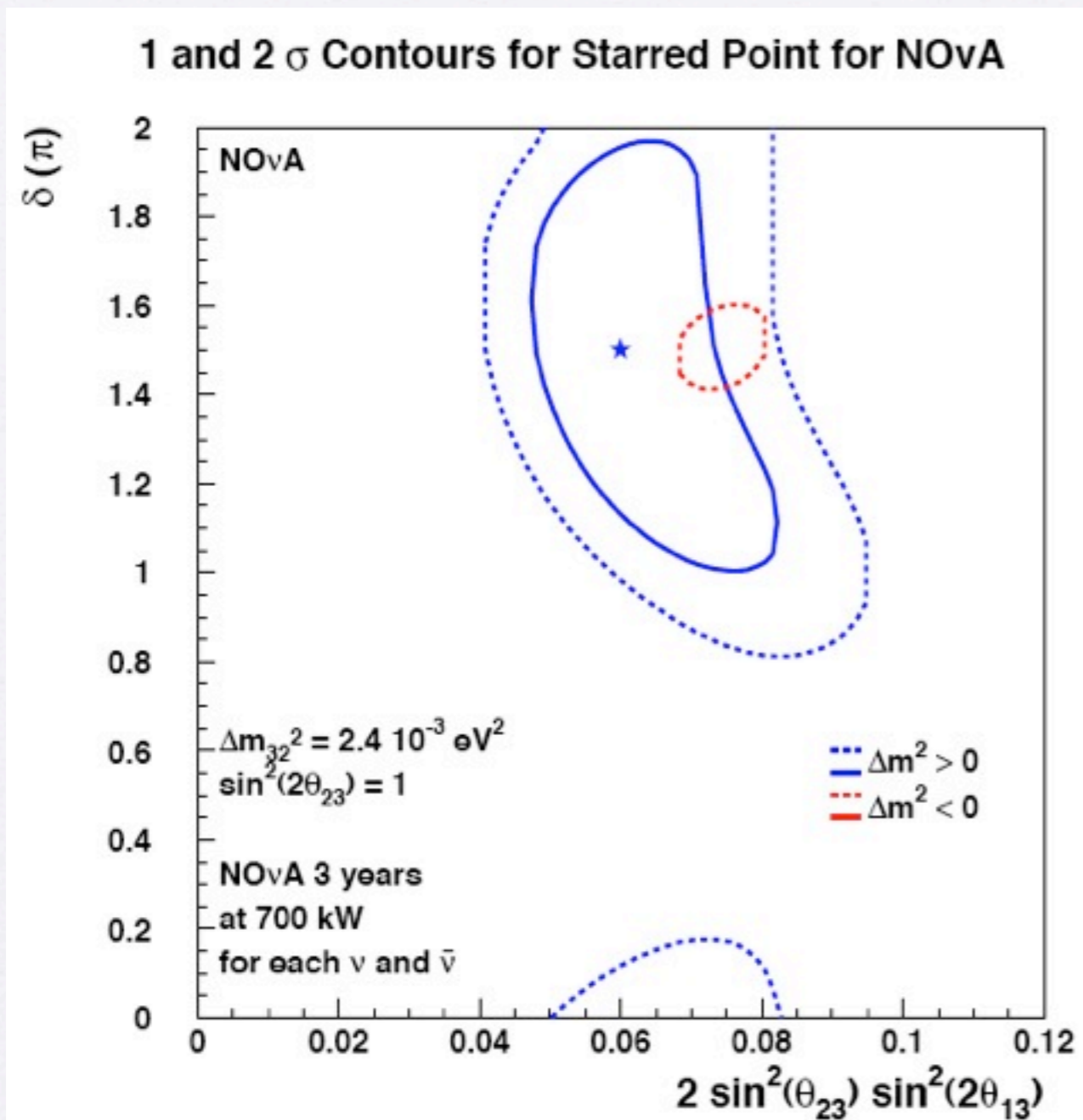
3.9cm

6.6cm

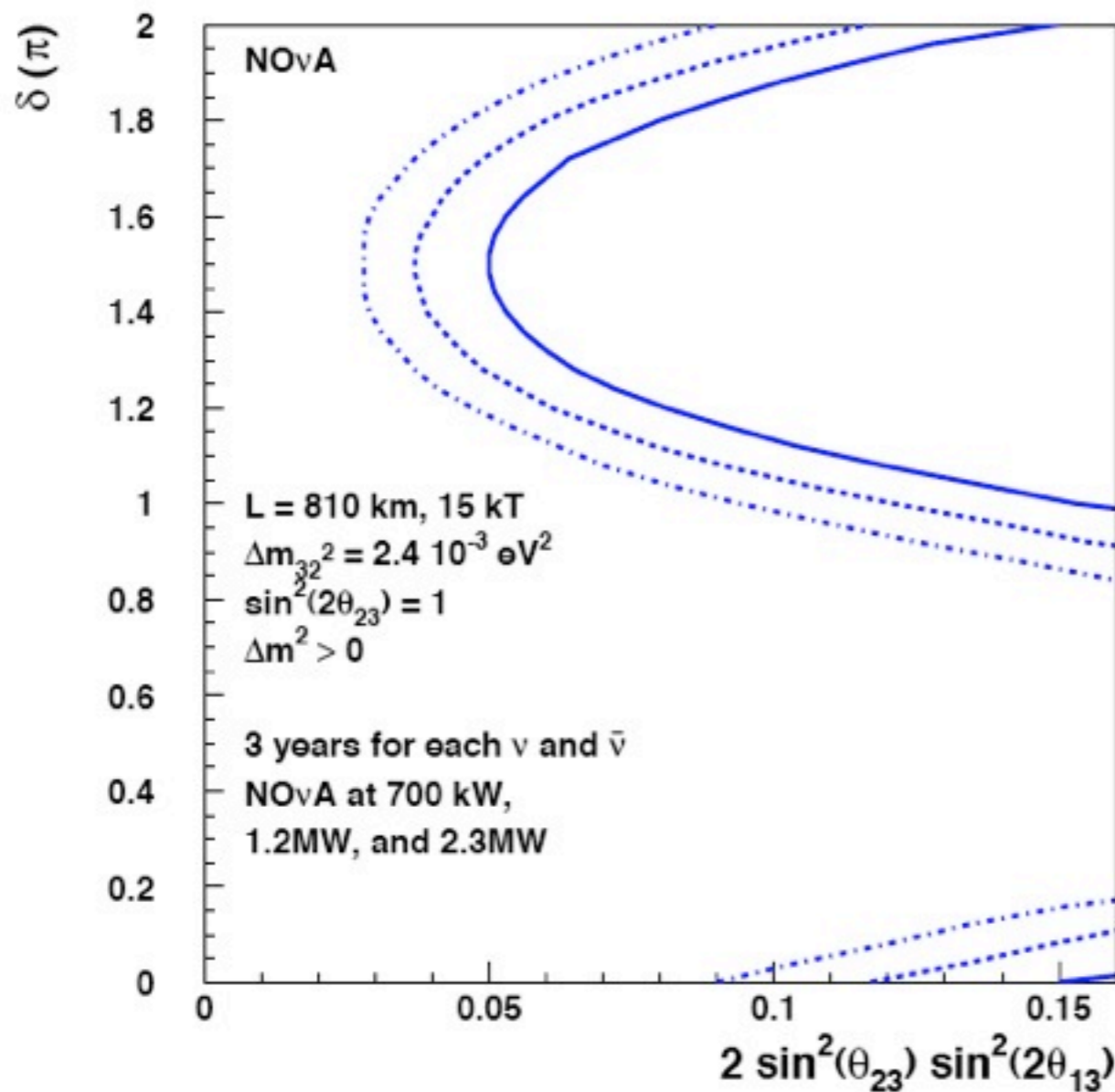
15.5m



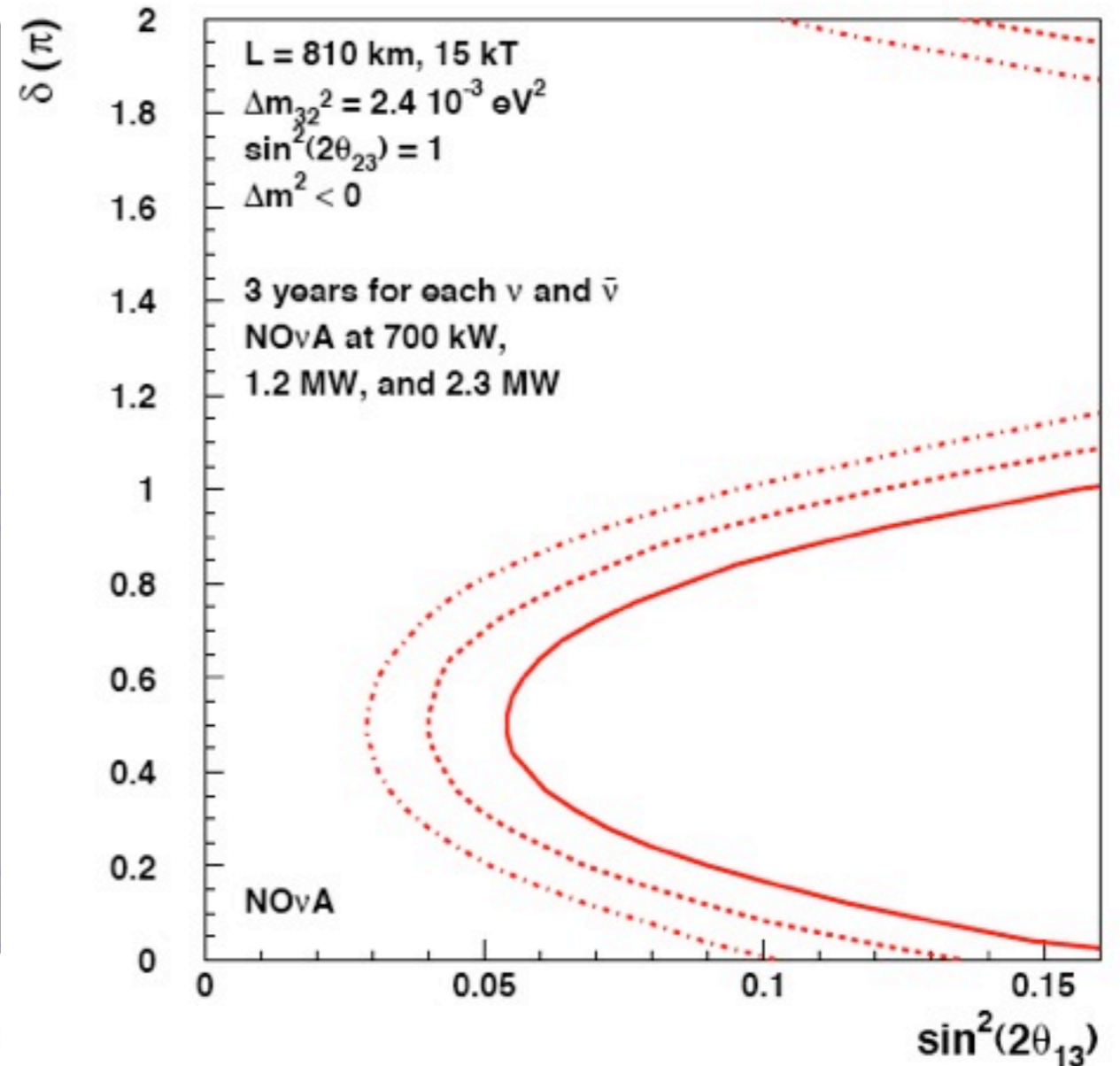
# $\delta$ vs. $\theta_{13}$ Contours: Examples



# 95% CL Resolution of the Mass Ordering NOvA alone

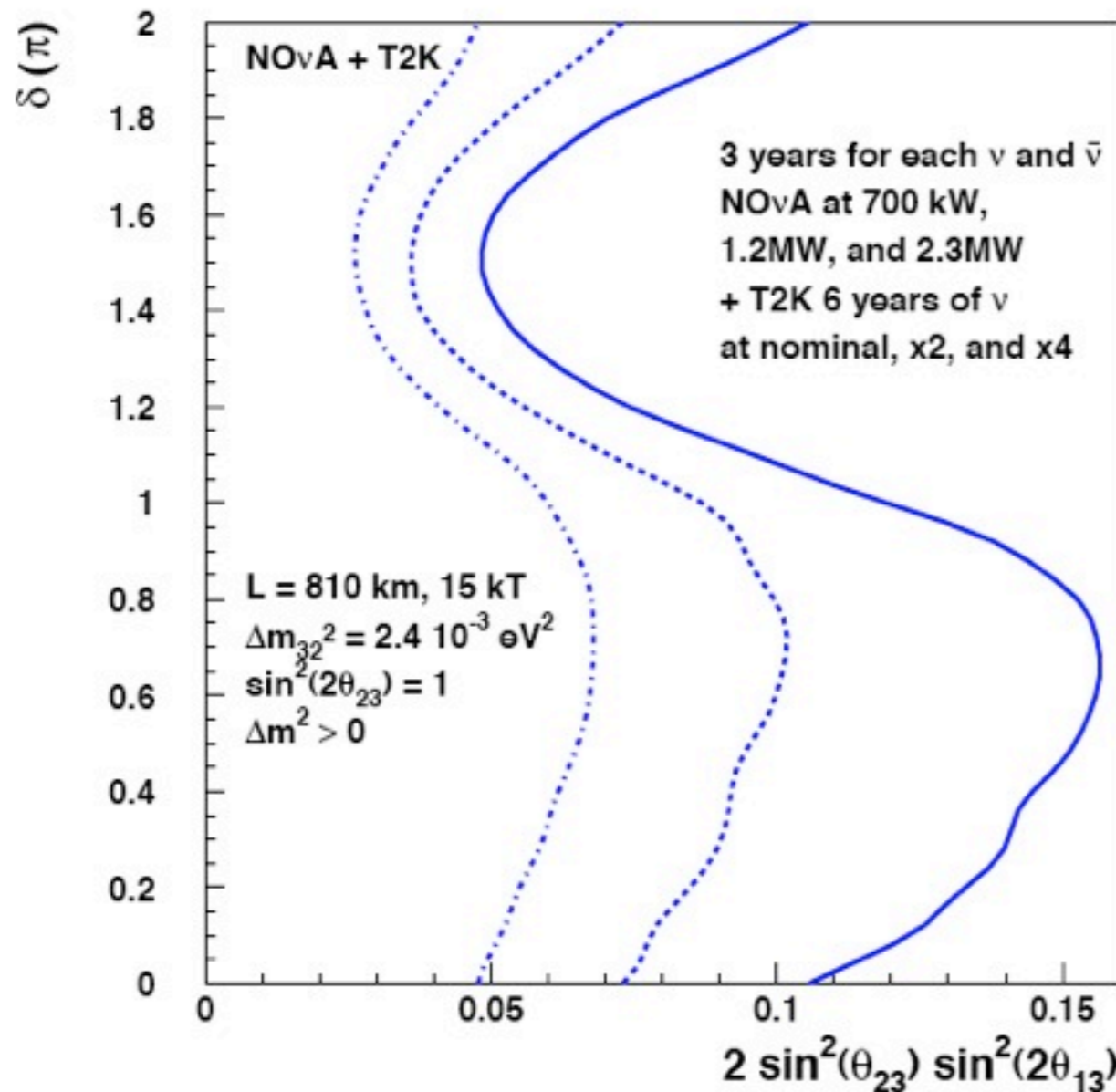


Normal hierarchy

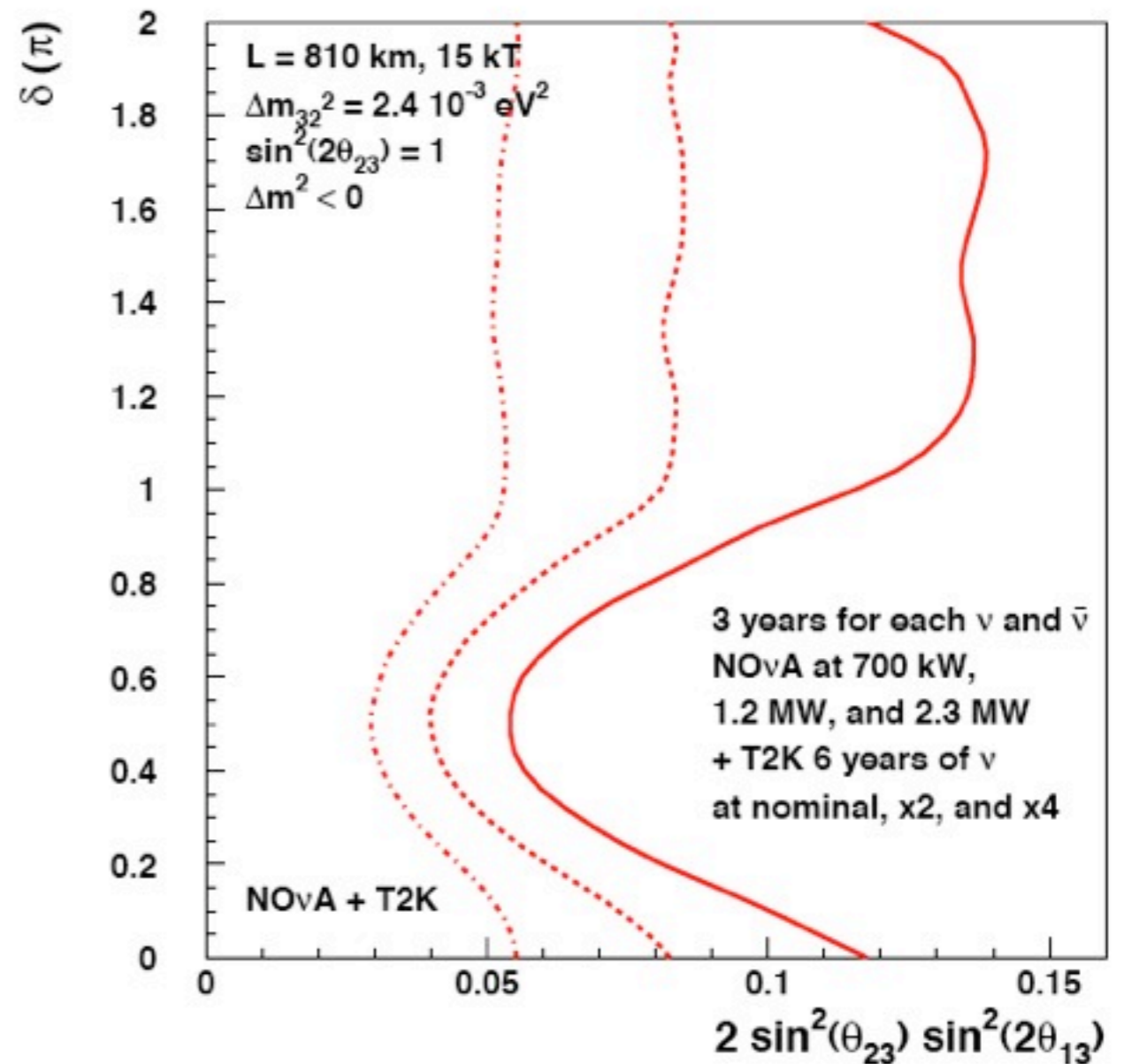


Inverted hierarchy

# 95% CL Resolution of the Mass Ordering NOvA + T2K



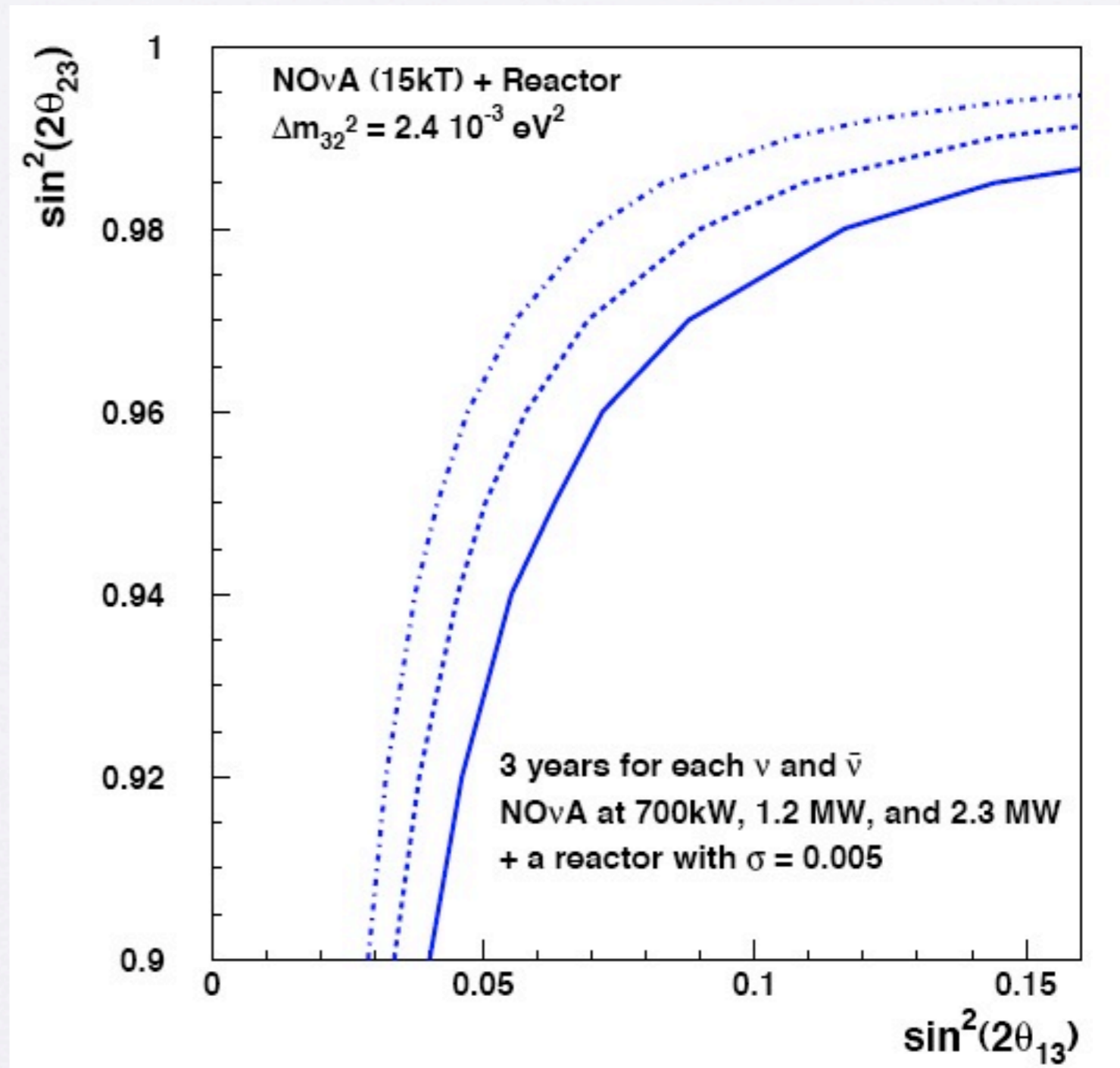
Normal hierarchy



Inverted hierarchy

# 95% CL Resolution of the $\theta_{23}$ ambiguity

- Ambiguity is resolved to the right and below the curves.
- Sensitivity depends on mass ordering,  $\delta_{CP}$ , and the sign of the ambiguity.
- Curves represent average over parameters.



# Proton plans

	Operating Conditions (May 2007)	Proton Plan Multi-batch Slip-stacking in MI	NOvA Multi-batch Slip-stacking in Recycler
<b>8 GeV Intensity</b> (p/Batch)	$4.3 - 4.5 \times 10^{12}$	$4.3 \times 10^{12}$	$4.3 \times 10^{12}$
<b>Number of 8 GeV Batches to NuMI</b>	7	11	12
<b>MI Cycle Time (sec)</b>	2.4	2.2	1.3
<b>MI Intensity</b> (protons per pulse or ppp)	$3.3 \times 10^{13}$	$4.5 \times 10^{13}$	$4.9 \times 10^{13}$
<b>MI to NuMI (ppp)</b>	$2.45 \times 10^{13}$	$3.7 \times 10^{13}$	$4.9 \times 10^{13}$
<b>NuMI Beam Power</b> (kW)	192	320	700
<b>Protons/year to NuMI</b>	$2 \times 10^{20}$	$3 \times 10^{20}$	$6 \times 10^{20}$
<b>MI Protons/hour</b>	$4.95 \times 10^{16}$	$7.3 \times 10^{16}$	$1.3 \times 10^{17}$

Expected  
NuMI  
operating  
conditions for  
NOvA

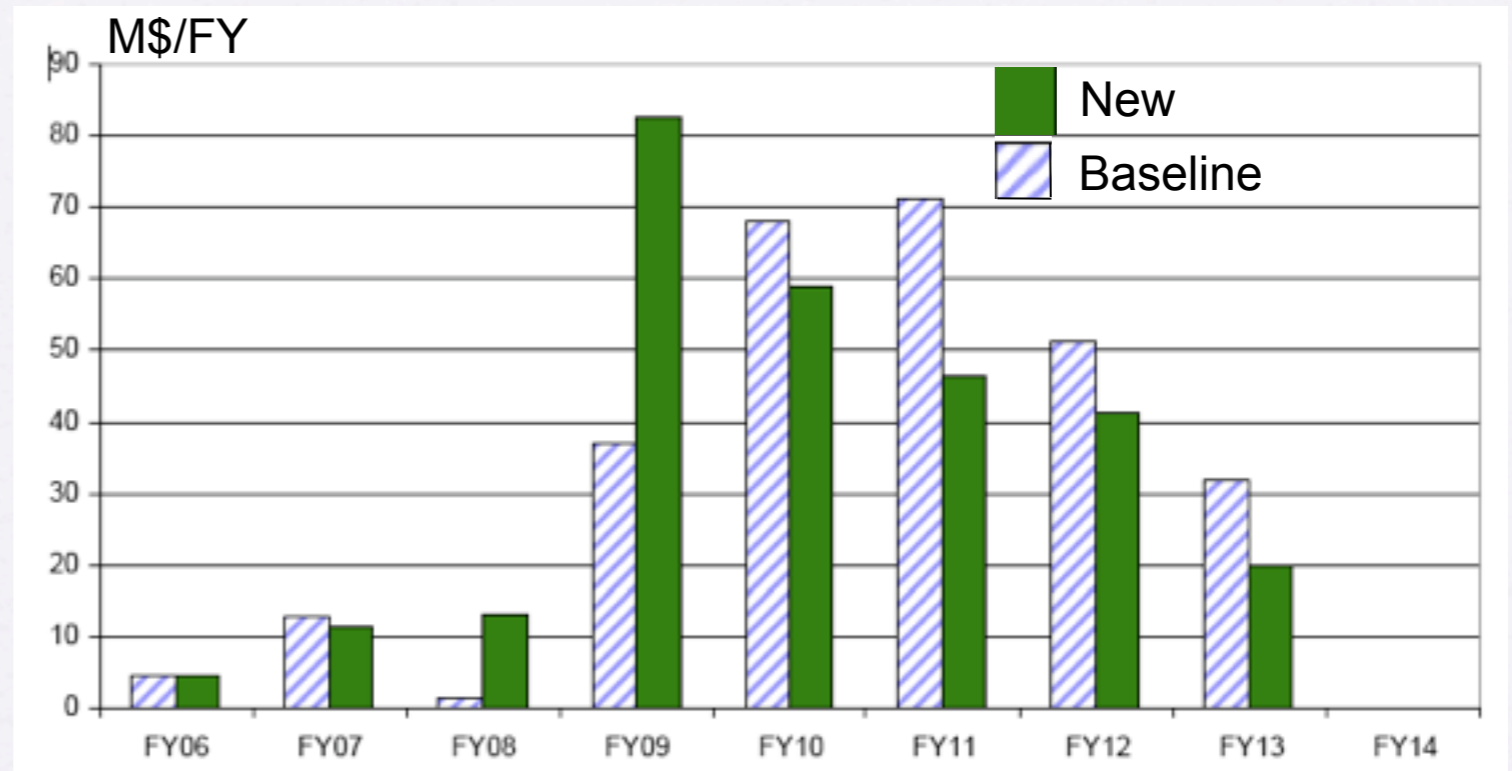
NuMI operating conditions for  
MINOS through summer 2007

NuMI operating conditions for  
MINOS fall 2007 to present



# NOvA Status and Plans

- NOvA has reached CD3a, CD3b is in the works.
- New budget is front loaded, new schedule reflects that:

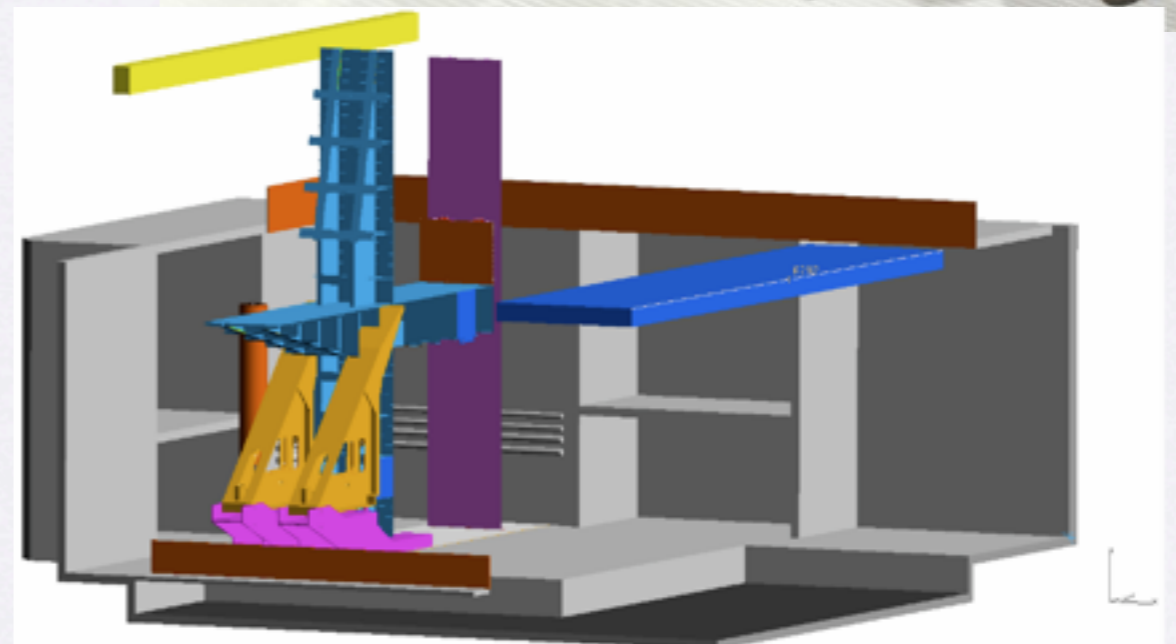


- Assembly R&D effort is in progress.
- Prototype Near Detector (IPND) will be installed on the surface next year sitting far off axis of the MINOS beam.
- Far Detector site ground broken and building construction has started.



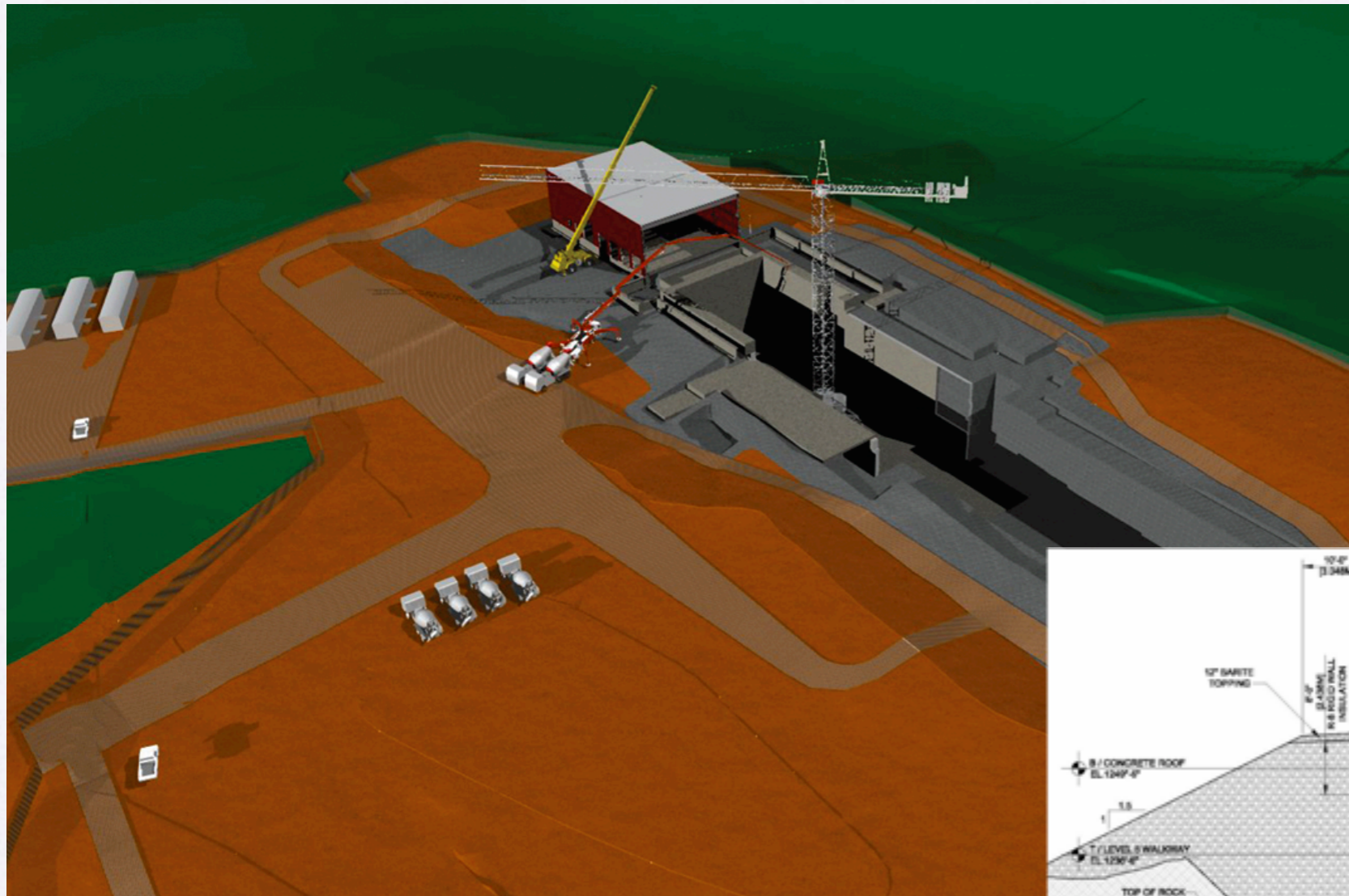
# Assembly R&D Effort

- Construction of the Full Scale Assembly Prototype (FSAP) was just completed at Argonne:
- Construction of 6 full size planes for time and motion studies and placement precision.
- Next will be the Full Height Engineering Prototype (FHEP) which will be mounted in the CDF building.





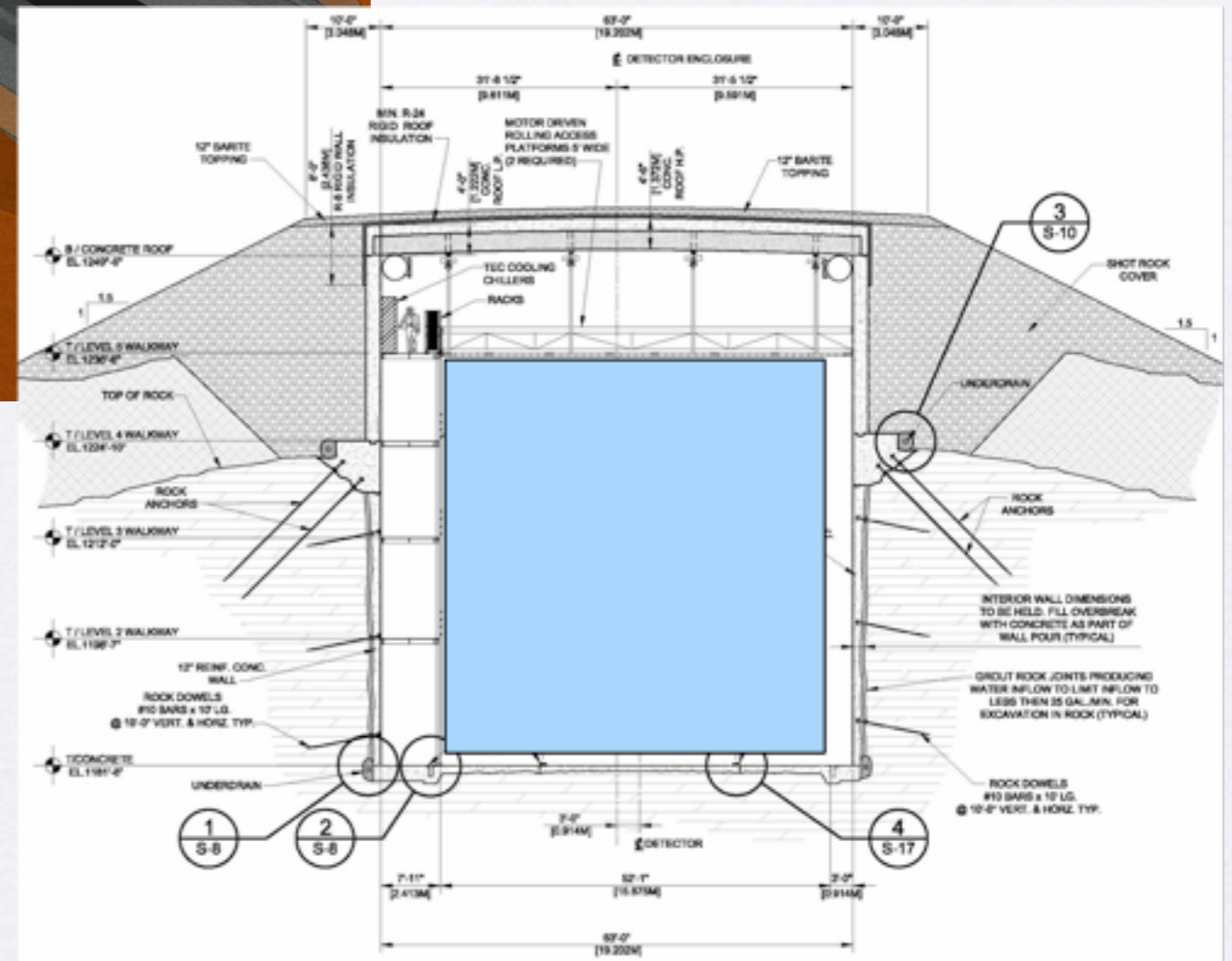
# Far Detector site



- Beneficial occupancy:
  - Assembly area July 2010.
  - Full building Nov 2010.

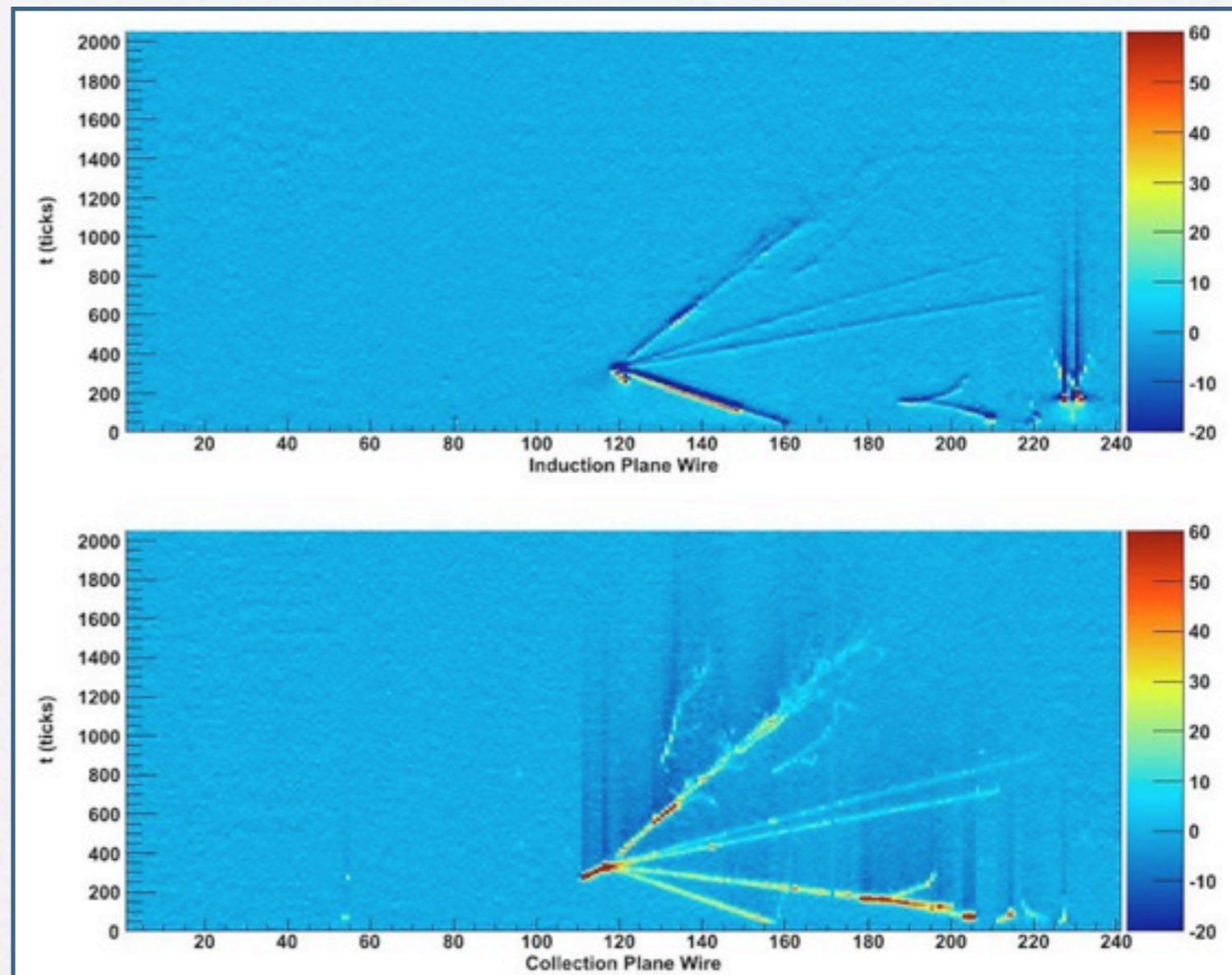
Expected Next Summer

- First 2.5 kT operational by Jan 2012. Full Far Detector operational mid-2013.



# Two proposed detectors

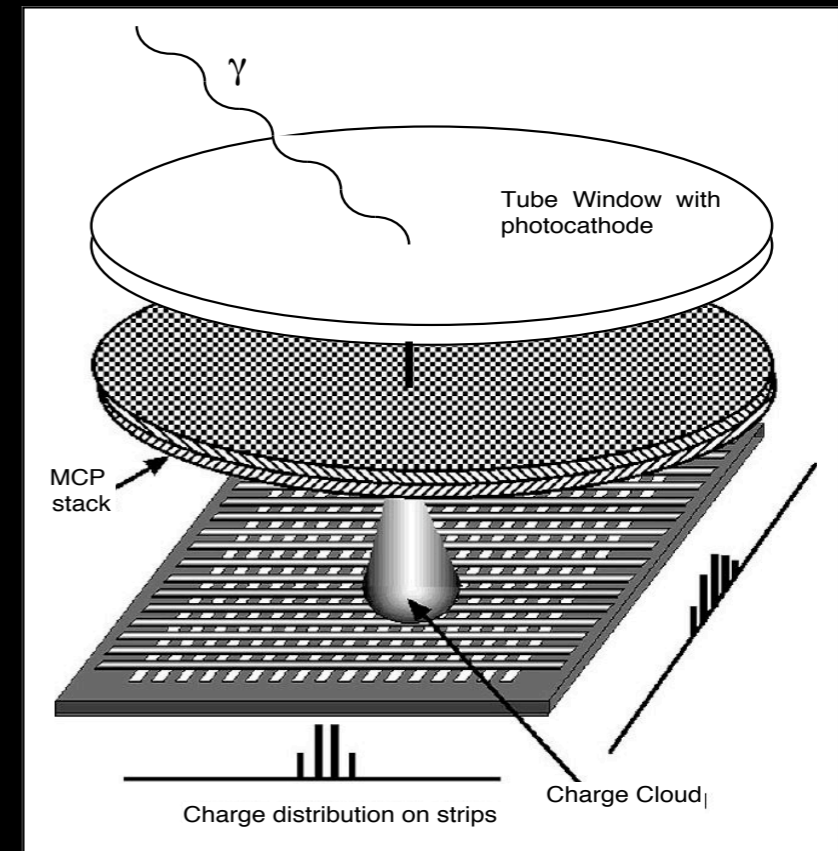
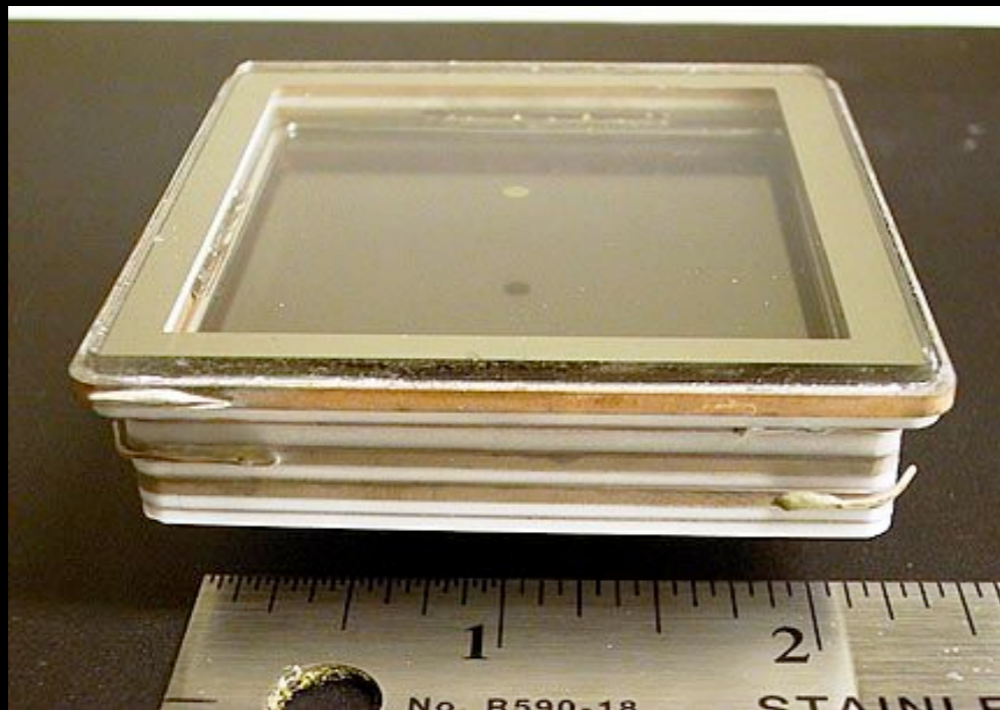
- Liquid Argon TPC as alternative or complementary detector.
- Initial detector 60 kton, modules of 20kton each?
- R&D program in progress, largest detector to date: 0.6 kT.
- Staged approach: ArgoNeut, MicroBoone, 5kT.
- Goal near-perfect efficiency and purity.
- Reconstruction algorithms in development.



ArgoNeuT first neutrino event!

# Fast Timing

- New Detector R&D Project
  - Collaboration between U of Chicago, 4 Divisions at Argonne, and several other Universities
  - Goal: provide cheap, large-area photo-detectors, with precision time resolution [ $O(1)$ - $O(100)$  psec, depending on the application].
- Based on Micro Channel Plate (MCP) technology

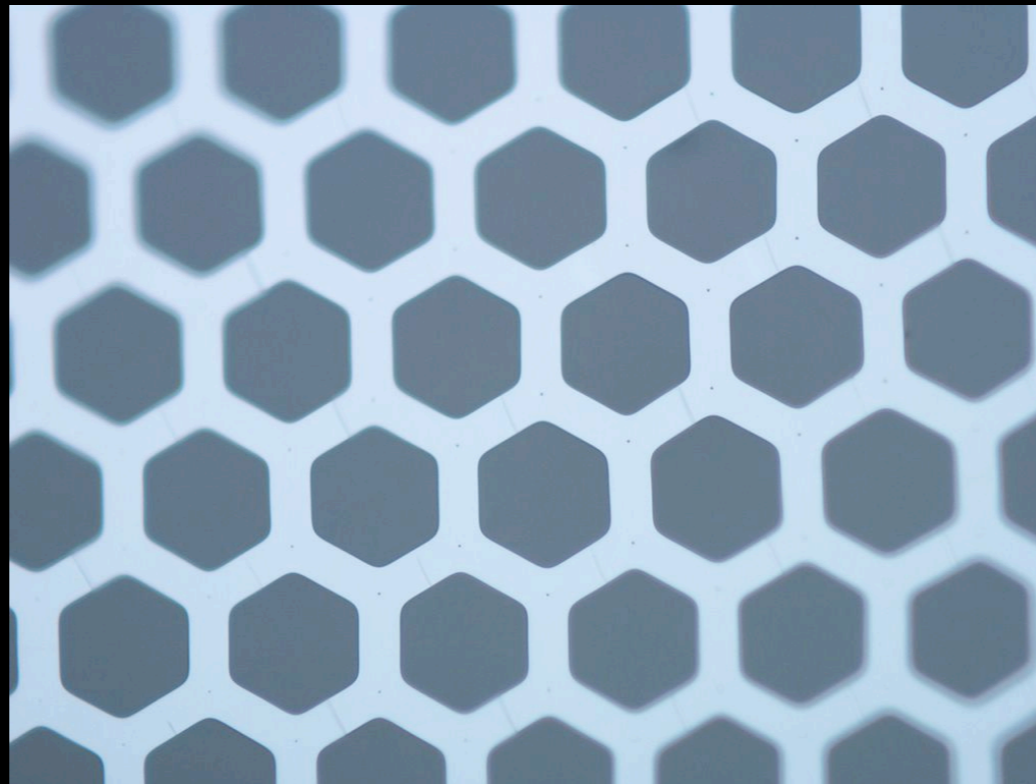


7/13/09

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# Fast Timing

- MCP's are traditionally expensive. Dynode pore-structures micro-machined out of ceramics.
- Our strategy:
  - Use cheap, batch methods to produce pore-structure (glass filters, Anodized Aluminum Oxide)
  - Use ALD to coat the pores with the appropriate semi-conductor materials.
  - Build into large-area plates with fast, custom front-end electronics.



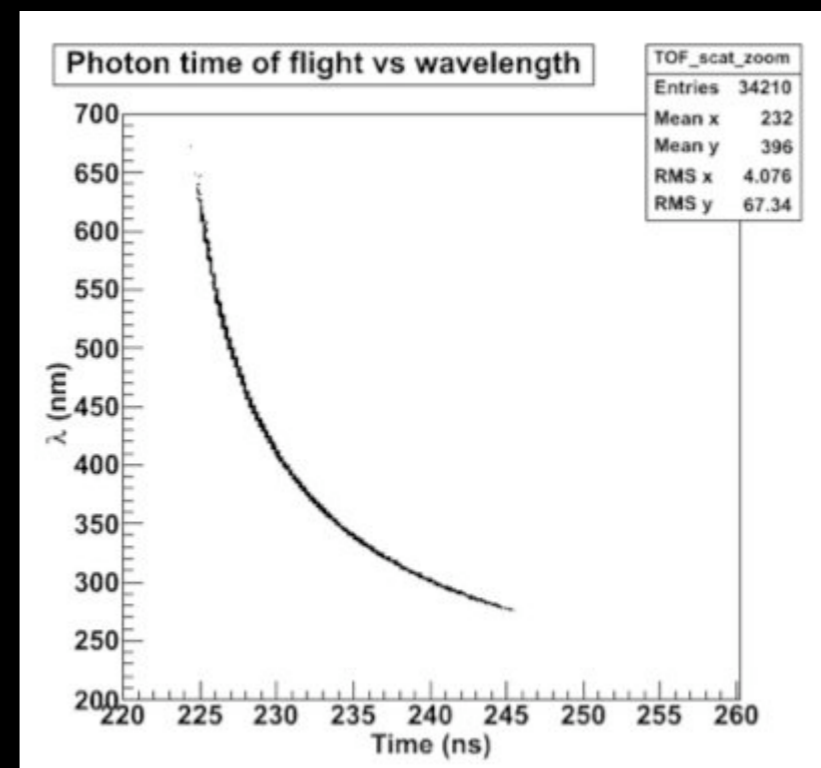
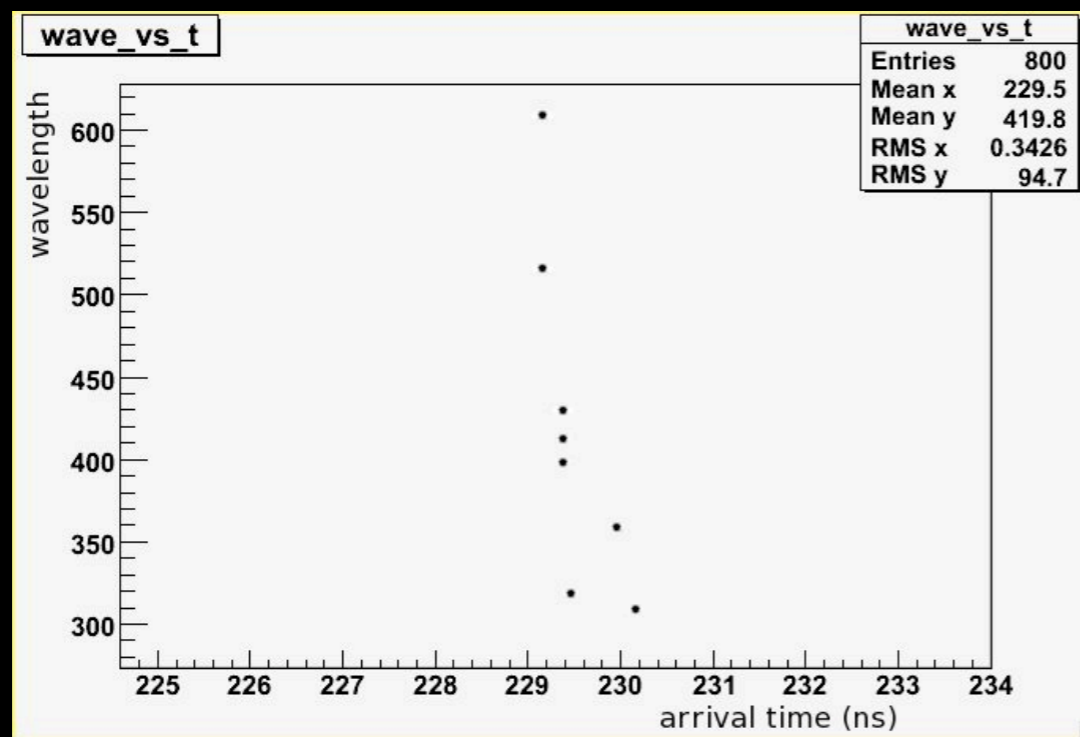
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# Fast Timing

- Group velocity versus wavelength in GEANT...
- Problems with how GEANT approximates  $dn/d\log E$



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